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Advancing Building bioclimatic comfort charts for hot developing countries as an early stage design tool

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Advancing Building Bioclimatic Comfort Charts for Hot Developing Countries as an Early Stage Design Tool

BY

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Declaration

The author wishes to declare that, except for commonly understood and accepted ideas, or where specific reference is made to the work of others, the content of this thesis is her own work. This thesis has not been submitted in part or in whole, to any university or institution for any degree, diploma or other qualification, with the exception of some content in chapter 4 only that had previously informed part of my Master degree at the University of Bath

Dedication

In the past four years, Syrians lived in fear and terror, ten million of them were displaced, including me, but I was the luckiest of all refugees. I didn't drown in the Mediterranean and I didn't lose a limb under a barrel bomb. I didn't freeze to death in a tent nor did I starve. I wasn't tortured and I wasn't raped. I had a chance to live, to study, to work, to love and to smile. I hope that I deserve this chance in life; I also hope that I will be able to help the unlucky ones, but for now I want to say; to all the children of Syria, and to all the innocent souls that were lost…

To the victims of torture and rape, and to all the prisoners of conscience …

To the heroes and survivors…

I'm sorry

To Syria, for a better future.

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Abstract

Developing countries in the Eastern Mediterranean basin have very limited resources for environmental appraisal. Shortage in power supplies, and poverty, mean that there is a great incentive to achieve thermal comfort in buildings at low cost. Passive cooling strategies, such as natural ventilation have the potential to achieve comfortable internal conditions without the expense of additional systems.

In order to enable architects to assess the potential for passive strategies, and make informed design decisions, pre-design informative tools are needed. Givoni's building bio-climatic charts BBCC are an example of such tools that allow architects to select a passive cooling strategy based on its cooling potential for the studied climate, however, little research has been done to test their efficacy.

This thesis establishes a new bioclimatic zoning for the Eastern Mediterranean region and determined the limitations and deficiencies of the BBCC by assessing their applicability for the studied region. Full building thermal performance analysis of two best practice domestic buildings, using dynamic modelling software IES VE 2013, indicated that day time and night time ventilation boundaries as proposed by Givoni were not reliable and that differnt means of expressing the potential of natural ventilation were required.

New guidelines and charts advancing Givoni's BBCC, were developed prescribing where there was scope to adopt day time and night time ventilation, considering both localised climatic conditions and typical practice in the region. Environmental monitoring of best practice domestic buildings was also conducted and the results were compared to both the dynamic modelling and the suggested guidelines.

The proposed guidelines in this thesis are expected to be of increased relevance considering the recent unrest in the studied region and the extent of reconstruction envisaged over the next few years.

Chapter 1: Background to research

Interest, and subsequently research, in the subject of sustainable and low energy architecture in developed countries has been increasing over the past few decades, less so in developing countries. However, Melchert (2007) argues that sustainable development should be a greater priority in developing countries than in developed ones due to issues associated with the environmental impact of buildings, such as health issues, pollution, dense urban spaces, and shortage in power supplies. In addition, developing countries suffer from poverty and economic problems, meaning that comfort in buildings should ideally be achieved at low-cost. People who do not have enough financial resources should not have to suffer from poor internal environments in buildings. Also in countries such as, Lebanon and Syria, that have experienced or are still experiencing wars, the infrastructure is severely damaged, resulting in unreliable energy networks.

According to the UN Agenda 21 (CIB & UNEP-IETC, 2002), the majority of the developing world has yet to be constructed. The Agenda also illustrates that most cities in the developing world are rapidly growing with limited access to funds making sustainable and affordable housing a pressing prerequisite.

The rapidly increasing population and housing demand in developing countries, the associated increase in the energy required, and the limited capacity of energy supply, make addressing the issue of reducing energy consumption in the building sector of utmost importance. Yet, most developing countries do not have strict or formal building energy regulations (see Figure 1.1). Building energy regulations in developed countries are driven by their commitments to the Kyoto protocol and The European Performance Building Directive (EU Parliament, 2002) to reduce their CO_2 emissions. Such regulations are constantly updated to meet reduction targets, while developing countries have non-binding commitments to the Kyoto protocol and thus no obligatory CO_2 reduction targets. Developing countries are also allowed greater freedom to increase their energy consumption in order to meet their economic and infrastructure development targets. Such targets are more important for these countries than reducing CO_2 emissions because they are more vulnerable to climate change-related hazards than developed countries are (Ward and Shively 2012, Niu et al., 2011).

Therefore, in the absence of government incentives such as subsidies and grants to promote energy efficiency measures, and in countries where the energy infrastructure is unreliable, low cost strategies that don't result in any additional costs such as passive design strategies may provide a better alternative. Such an alternative could be favoured by consumers, architects and contractors alike, who wish to reduce the energy demand and costs of their buildings, and to enhance the internal comfort conditions at low cost. Unfortunately very limited resources and knowledge is available for them in this area. Any proposed passive strategies should be incorporated in the building design from the early stages. The following sections will explain why, and will outline the scope of research in this thesis.

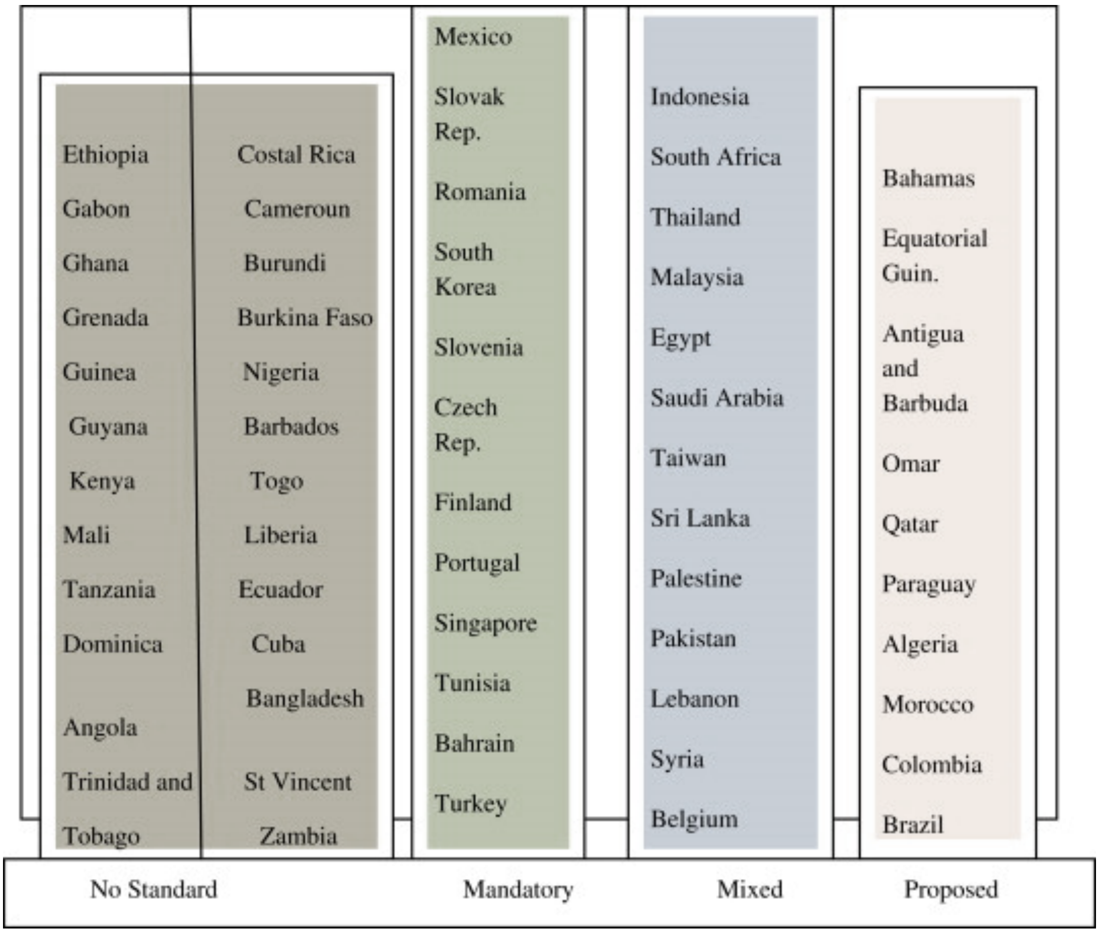


Figure 1.1: Status of Building Energy Standards development and adoption in 60 developing countries, (Iwaro and Mwasha 2010).

1.1 The design process:

It is generally believed that the design process as a cognitive activity is a problem solving (Visser, 2009) or a decision-making process (Shoshkes, 1990), that includes a series of decisions in order to generate a solution.

Although designers do not follow a definite or systematic procedure when designing (Visser, 2009), it is also widely accepted that all design projects follow the same process at a general level (Shoshkes, 1990). The method by which designers achieve the most optimal solution varies depending on their expertise, the project complexity, and its management (either in individual or collective design). They may follow a top-down or a bottom-up approach (Visser, 2009), or they may resolve sub-problems in order of importance, with each solution generated imposing a restriction on subsequent sub-problems to be tackled. Others may produce solutions to sub-problems and later try to generate a composite solution (Simmonds, 1980). However, it is widely accepted that the design process is divided into work stages that increase in complexity and level of detail, meaning that, by the end of each stage new constraints on the design are implemented, (Petersen and Svendsen 2010). Petersen and Svendsen, (2010), cited Ostman, (2005), and summarised the main design phases into: conceptual design, main design and detailed design. This design process, i.e. starting with designing the building as a whole and then working through details in a “top-down” design procedure, has evolved and remained the same over time and it is not expected to change dramatically in the future, (Ellis and Mathews, 2001). Thus, poor design decisions taken at the early stages can result in delays and increased overall costs, (Shoshkes, 1990).

According to Shoshkes (1990) these early design stages are:

- planning
- programming
- schematic design
- design development
- contract documentation
- Contract administration

This is also reflected in current planning guides. For example national institutes of architects such as the RIBA, (2013), divide the design process into stages in order to organise it. For instance, according to the UK RIBA plan of work the design process is divided into five stages, (0: strategic definition, 1: preparation and briefing, 2: concept design, 3: developed design, 4: technical design), followed by construction-related stages, however, these five stages fall under three main categories; preparation (stages 0 &1), design (stages 2 & 3) and pre-construction (stage 4).

Architects or the lead building designers are directly responsible for early design decisions, and their input decreases as the project develops. Later stages such as technical design are managed by specialists such as structural, mechanical and electrical engineers. Design decisions taken at the early stages of building design process have the greatest influence on the energy performance of the building, (Petersen and Svendsen, 2010; Attia et al., 2012). This has been illustrated in the past decades by the work of numerous researchers, (Baker and Steemers, 1996; Bogenstätter, 2000; Ellis and Mathews, 2001). The early design stages include a series of design decisions such as the overall shape, plan and orientation of a building, that are directly related to the resultant energy consumption and thermal performance of buildings. Later, designers specify building details, that also contribute to the overall performance of buildings; however later decisions are easier to modify than early stage decisions (Baker and Steemers, 1996; Weytjens and Verbeeck, 2010). The energy performance assessment is usually done by a specialist or an engineer, usually leading to extensive amendments in the original design in order to meet specified or desired performance criteria, (Schlueter and Thesseling 2009).

Therefore, architects who want to adopt a low-carbon or energy efficient solution should have the facility to examine the potential of adopting such solutions from the initial stages, i.e. the conceptual design phase, (Ellis and Mathews 2001; Attia et al., 2012). However, there are few tools available for architects and designers that evaluate the potential environmental performance of a building at such early design stages, (Attia et al., 2012).

Detailed dynamic-simulation tools are more common than informative pre-design tools, but such whole building simulation tools are unlikely to be used by architects early in the design process, because they require more building description data that is only available to architects at later stages, (Baker and Steemers, 1996; Weytjens and Verbeeck, 2010; Attia et al., 2012). Although there has been a rapid development in the quality and quantity of building simulation tools over the last decades, they are still inefficient at supporting design decision-making; rather they are often used as post-design evaluative tools (Petersen and Svendsen, 2010). As a result, when thermal analysis is undertaken, major design decisions have already been made, making amendments to the original design more difficult and costly. Furthermore, dynamic simulation tools require specialist knowledge and training with modelling budgets available only to larger established architectural practices. Small practices, i.e. less than 50 employees, (EU commission, 2003), do not have the time or resources to devote to this level of analysis. Most Architectural practices in developing countries tend to be small. Micro enterprises, i.e. less than 10 employees (EU Commission, 2005), especially informal ones, dominate the economic activity in most developing countries, (International labour organization, 2009).

Regardless of the apparent importance of promoting early-stage or pre-design tools, a study by Attia et al. (2012), indicated that 90% of available building performance simulation tools were “post-design evaluative” tools and used by engineers and other “non-architectural” specialists. Less than 1% were “pre-design informative” tools for architects. The findings of Weytjens and Verbeeck (2010), survey suggested that the main reasons for the failure of integrating building simulation tools into the design process was that architects considered these tools outside their core competencies, too complex to operate, and time consuming. Ninety per cent ranked “ease of use” as the most important criteria for energy evaluation tools. Many researchers have addressed the gap in integrating building performance tools in the design process at early stages (Ellis & Mathews, 2001; Bleil de Souza, 2009; Petersen & Svendsen, 2010; Attia et al., 2012). However, few have considered developing pre-design informative tools that architects can relate to when drawing the initial sketches of a design without the need to expand their scope of knowledge and speciality. Additionally, those few tools available were developed in the 1990s, 1980s or earlier, which indicate that current research is more focused on developing computer based tools.

Crucially, most of the available tools have been developed in, and for, developed countries, with fewer environmental appraisal tools available in low and middle-income developing countries. By ranking countries by building energy assessment tools use, (US DoE, 2013), against the countries' economic classification, (World Bank, 2011)[1], it could be concluded that 75% of building energy tools are used in developed countries. The reason for this could be that building energy regulations are the most influential factor over the design process, the integration of environmental solutions, and consequently the use of resultant energy tools adopted, forcing architects and designers to assess the energy consumption of their designs, (Weytjens and Verbeeck, 2010; Schlueter and Thesseling, 2009).

More to the point is that the design process is more structured in developed countries. For instance, the UK RIBA "green overlay" to the RIBA plan of work is designed to ensure that low-carbon strategies are integrated into the design process and the use of building energy modelling is required to assess the expected energy performance of buildings before they are built and used, (RIBA, 2011).

Given the lack of national drivers, an organized design process that promotes the use of energy tools, and the small number of large architectural practices that may consider adopting low energy solutions in developing countries, highlights the importance of "easy-to-use" pre-design informative tools for the developing world.

1.2 The proposed approach

Two approaches are commonly used for pre-design tools; the first is the bio-climatic approach that evaluates the performance of a building in regards to thermal comfort conditions. The second is to estimate the energy consumption from the early stages. An example of the latter is the LT method (Baker and Steemers 1993), which relies upon the concept of passive zones. It can provide an estimation of annual primary energy consumption for heating, cooling, ventilation and lighting based on parameters that are available at early design stages, such as orientation and glazing ratios. The first approach was chosen for this research as it is more suitable in the context of developing countries, where energy consumption per capita is not comparable to that in developed countries and in which occupants' well-being is often given less consideration is design of the internal environment. Additionally, preliminary building design information is required before using

[1] *World Bank considers all low-and mid-income countries as developing.*

tools that estimate energy consumption, while the bioclimatic approach offers informative pre-design guidelines for architects. Furthermore, by achieving comfortable conditions through passive strategies, energy consumption will be reduced accordingly. Givoni's building bioclimatic chart (BBCC), (Givoni, 1976) is such a pre-design informative tool. It suggests comfort boundaries for passive and low energy cooling strategies without air conditioning in hot climates, namely, natural day or night ventilation and evaporative cooling. Givoni's bioclimatic building charts were developed based on research conducted mainly in, but not limited to, the USA (California and Arizona), Europe (Spain) and Israel. A general characteristic of these regions is that they share a Mediterranean (Warm-temperate climate with dry hot summers according to Koeppen-Gieger climate classification), and hot-arid climates, see Figure 1.2.

Except for the northern shore of the Mediterranean (Europe) and Israel, countries in the Mediterranean basin region are characterized as developing countries, (World Bank, 2012). This offers a significant opportunity to compare the charts for hot developing countries that share similar climatic and geographical location with the developed countries where Givoni conducted his research in. A detailed review of the deficiencies of the charts and their applicability for the Eastern Mediterranean EM region are presented in the following chapters.

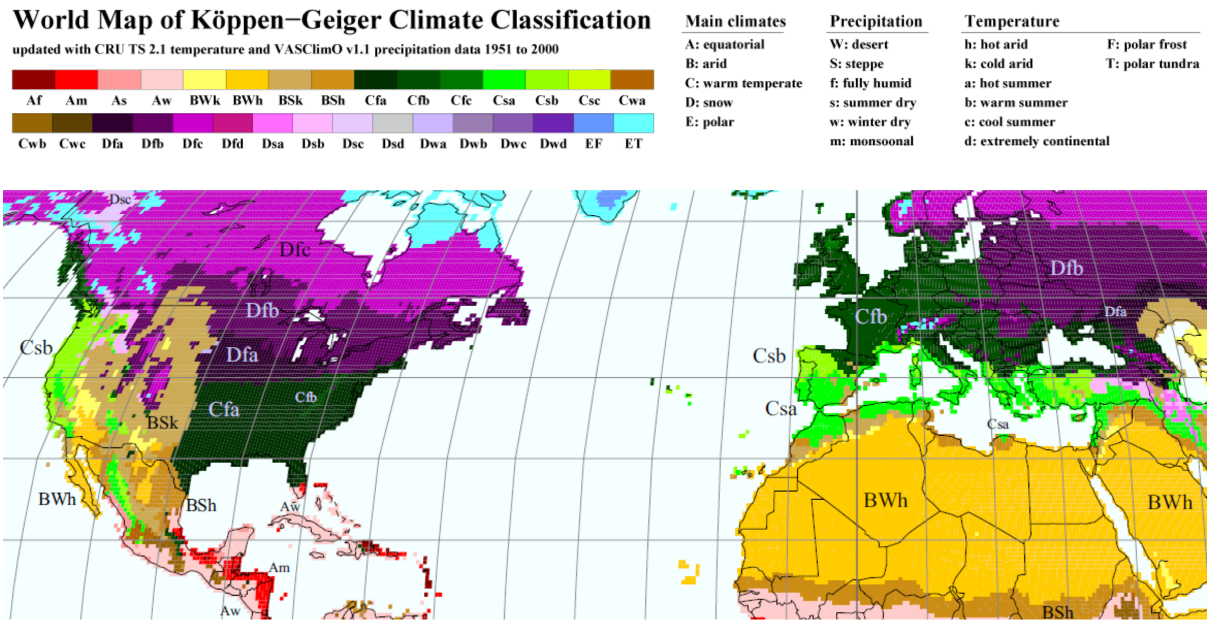


Figure 1.2: World map of Koeppen climate classification shows the distribution of warm temperate climate (C) and arid (B) in the Mediterranean basin region and Western USA (Kottek et al., 2006).

1.3 Boundaries and limitations

This research is directed at architects and is limited to hot developing countries in the Eastern Mediterranean, namely, Syria, Lebanon and Jordan. This research is also limited to passive cooling strategies such as natural ventilation for residential buildings. Figure 1.3 illustrates the suggested boundaries and limitations of this study.

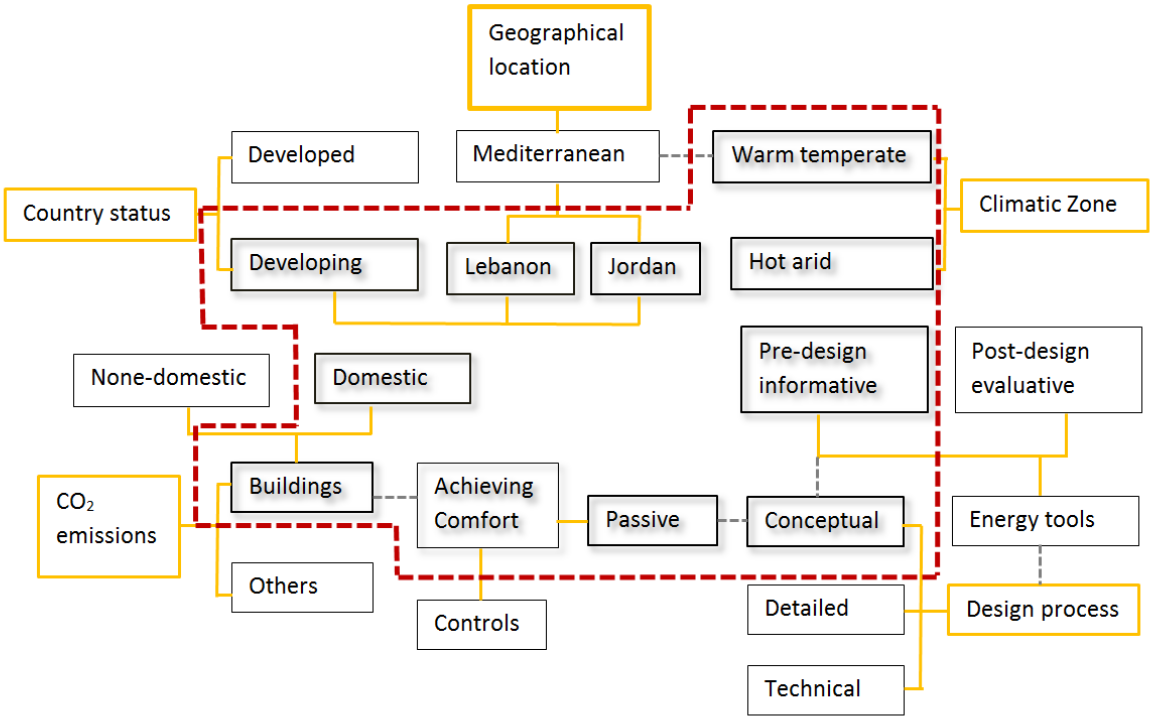


Figure 1.3: Scope and limitation of the research.

1.4 Contribution to knowledge

This thesis tested the validity and applicability of Givoni's BBCC for Eastern Mediterranean climates. The results of this research are intended to serve as guidelines for architects, in the selected countries, that are both user-friendly and supported by analytical and experimental investigation. The guidelines are presented in the form of graphs and tables that are based on Givoni's (1997) and the experimental work conducted in this thesis. The graphs help to establish the extent that thermal comfort can be enhanced by applying a given passive design strategy, namely natural ventilation. Thus, by quantifying and understanding the influence of relevant design parameters on occupant comfort and well-being, simple passive environmental design strategies are facilitated in developing countries. Consequently, this research aims to reduce the negative impacts of the rapid development or the reconstruction that these countries are undergoing by offering the architects and the clients and all of those involved in the design process an opportunity to make informed design decisions.

1.5 Objectives and Research Methodologies

The above aims were achieved through the following objectives summarised in Table 1.1

Table 1.1: Research objectives and methodologies

OBJECTIVE (CHAPTER NO.)	METHODOLOGY	OUTPUT
Review existing bio-climatic design tools to establish a baseline in current practice. (chapter 2)	Desk-based study	Identify limitations in the use of early stage design tools. Define knowledge gaps in bio-climatic design tools in use.
Assess the suitability of passive cooling strategies for eastern Mediterranean climates using BBCC. (chapter 3)		Identify thermal comfort zone/s for the Eastern Mediterranean region to define boundaries that passive cooling design strategies seek to achieve. Assess the applicability of BBCC
Define reference buildings for selected hot climates. (chapter 4)		Select best practice domestic buildings as exemplars of 'well-designed' buildings and map applied passive strategies to those considered in the BBCC.
Test the BBCC predictions for the selected passive strategies and buildings. (chapter 5)	IES dynamic Modelling	Comparison between best practice domestic buildings as exemplars and BBCC predictions. Evaluation of sensitivity and uncertainty during dynamic modelling. Recommendations for appropriate day and night ventilation.
Undertake parametric analysis of design options.		Establish how selected design options, (e.g. traditional Vs best practice

(chapter 6)		construction of building elements and solar shading), affect overall passive cooling performance.
Monitoring of selected reference buildings. (chapter 7)	On-site experimental monitoring.	Undertake post-occupancy performance monitoring to compare/support modelling predictions.
Examine the performance gap between simulations and monitored data. (chapter 8)	IES dynamic modelling	Appraise significance of discrepancies between simulated and monitored results on recommendations for appropriate day and night ventilation.
Suggest appropriate ranges for the applicability of the selected passive strategies in the eastern Mediterranean region.	Desk-based study	Easy to use guidelines in the form of series and graphs for Architect in the Eastern Mediterranean region

Chapter 2: Literature review

This chapter will review existing literature on Givoni's bio-climatic charts, their limitations and known deficiencies so that the key knowledge gaps may be determined.

2.1 Building bioclimatic charts:

The following is a review of the most common bioclimatic design tools.

2.1.1 Olgyay bioclimatic charts 1963

The first bioclimatic chart was developed by Olgyay, (1963). The comfort range, the underheated and overheated conditions, and the ability to extend the comfort zone according to wind speed, water evaporation and solar radiation were plotted on the same chart. However, Givoni argued that these guidelines were based on outdoor conditions and therefore, may lead to a flawed estimation of the real needs when considering the actual indoor temperature that may differ significantly depending on the building thermal mass.

2.1.2 Givoni's building bio-climatic charts 1976 (BBCC)

The BBCC were based on expected indoor building temperatures. The chart suggests comfort boundaries for passive and low energy cooling strategies without air conditioning in hot climates, plotted on a conventional psychometric chart. These cooling strategies are; daytime ventilation, high thermal mass, with and without, night-time ventilation, direct evaporative cooling and indirect evaporative cooling by roof ponds.

2.1.3 Evan's comfort triangles (1988)

Evan's Comfort Triangles is a graphical tool developed for the Argentinean climate. It defines comfort zones for different activity levels, and it allows the representation of climatic variables in relation to monthly average temperatures and temperature ranges. Bioclimatic design strategies can then be selected according to temperature ranges as they determine the need for cross ventilation or thermal mass.

Givoni's charts were selected in this research as they evaluate design strategies in terms of internal thermal comfort rather than energy consumption and because they are not country-specific as they address both developed and developing countries. While Evan's triangles are more limited, the Givoni charts are a developed version of Olgyay charts.

2.2 Givoni's Building Bio-climatic charts

The building bio-climatic charts, (BBCC), were first developed in 1976 by Givoni to address the aforementioned limitations of the Olgyay bioclimatic charts. The BBCC were based on expected indoor temperatures in buildings, with no mechanical cooling, using the index of thermal stress. The comfort zone for acclimatized people at rest was plotted on a conventional psychrometric chart as shown in Figure 2.1. Psychometric charts are a graphical method to express the thermal properties of air and its ability to hold moisture. They are available for a range of atmospheric pressure and temperatures. They essentially allow a designer to illustrate the factors associated with thermal comfort for specific climatic conditions. The chart has a dry-bulb temperature scale on the horizontal axis, a humidity ratio (moisture content) scale on the vertical axis, and curved lines of relative humidity with an upper curved boundary that represents saturated air or 100 percent moisture holding capacity. The chart also shows wet-bulb temperature; enthalpy; and dew point or saturation temperature.

In addition the BBCC also outlined the boundaries of climatic conditions in which comfort could be achieved by applying selected strategies such as ventilation, evaporative cooling and air conditioning. The boundaries were based on research and field studies conducted in developed countries, namely USA, Europe, and Israel.

In 1992, Givoni proposed a revised BBCC, comprising a chart that outlined comfort boundaries for passive and low energy cooling strategies, without air conditioning, in hot climates. These cooling strategies were:

- i) Daytime ventilation
- ii) High thermal mass with and without night-time ventilation
- iii) Direct evaporative cooling and indirect evaporative cooling by roof ponds

Two sets of boundaries were suggested: one for developed countries and another for developing countries based on Givoni's "personal evaluation". For developing countries, he suggested an elevation of the upper limits of acceptable temperature and vapour content by 2°C, and 2gr/kg respectively, taking into account the acclimatization of the population to hot-humid conditions and the expected standards of living for people in developing countries. The following is a summary of the boundaries suggested for each strategy, (Givoni, 1992):

I) Daytime cross ventilation

Givoni suggested that daytime cross-ventilation is applicable when the maximum outside temperature is equal to or less than 28-32°C, (depending on people acclimatization), and where the diurnal temperature range is less than 10°C, assuming an air speed of 1.5 to 2 m/s. This was based on the hypothesis that the internal air temperature follows outdoor temperatures. Additionally, in an experimental study conducted by Givoni in Pala, California, in which day-time cross-ventilation was applied, it was found that high thermal-mass, well insulated buildings were able to maintain a temperature 2-3° lower than the maximum outdoor temperature, while low thermal-mass buildings' indoor temperatures followed outdoor temperatures.

II) Night time ventilation (nocturnal ventilation)

According to Givoni, nocturnal ventilation is only effective in high thermal-mass buildings and in regions where the diurnal temperature swing is more than 15°C. Assuming an air speed of 1.5 m/s Givoni suggested an upper limit of 36°C for developed countries and 38°C for developing countries in which nocturnal ventilative cooling is effective. A reduction in temperature is also recommended with increased humidity.

III) Direct evaporative cooling

Givoni suggested an upper limit of 42°C dry bulb temperature and 22°C corresponding wet bulb temperature for effective direct evaporative cooling and an additional 2°C increase for developing countries. The boundaries for developed countries were based on analysis of an experimental study by Cunningham and Thompson (1986) on a passive evaporative cooling tower. In addition to measured and computed results from experimental studies on the ‘shower-tower’ developed by Givoni initially for outdoor rest areas for the 92 EXPO in Seville, Spain; and later in buildings in Los Angeles and Saudi Arabia (Al-Hemidi, 1995).

IV) Indirect evaporative cooling

Unlike direct evaporative cooling, indirect evaporation decreases the temperature of the air without increasing its humidity and thus has a higher boundary. Based on several experimental studies, Givoni suggested that indirect evaporative cooling is applicable when the outdoor maximum dry bulb temperature is 44°C and the wet bulb temperature is 24° for both developed and developing countries because the higher heat gain through less insulated building envelopes might offset the effect of acclimatisation.

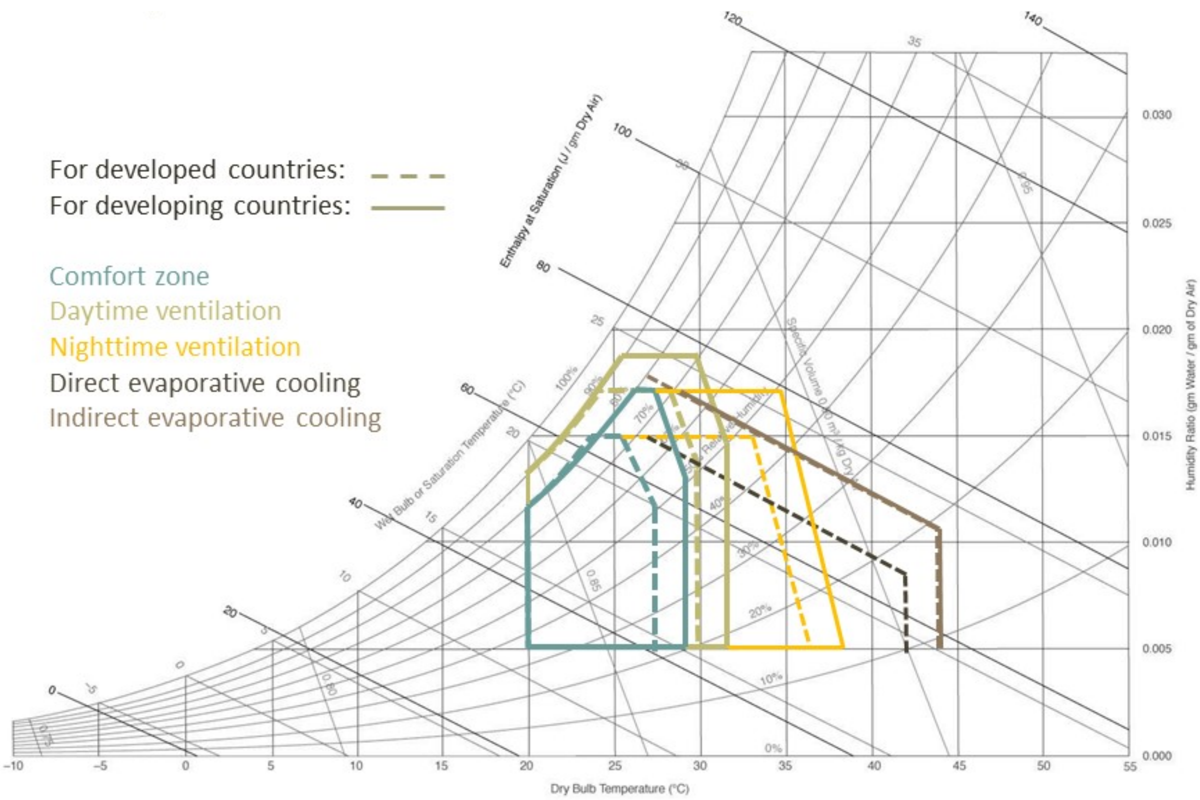


Figure 2.1: Different design strategies and boundaries of the passive cooling approaches for hot developed and developing countries.

2.2.1 The charts in current practice

A literature review by Visitask (2007) has shown that there have been considerable efforts to develop a computer-based version of the bioclimatic charts, such as Clayton (1987), Acenas (1989), Milne and Yoshikawa (1979), Li and Milne, (1994), Marsk and Raines, (1998), in addition to Roriz (2006). However, few studies were found that questioned the validity of the charts, for example (Lomas et al, 2004; Visitask, 2007). Givoni's charts were extensively used by researchers to develop bioclimatic zones in several regions such as; Jamal and Sayigh (1989) for Palestine, Sayigh and Marafia (1998) for Qatar, Zein-Ahmed et al (1998) for Malysia, Ajibola (2001) for Nigeria, Lam et al (2006) for China, Mahmoud (2011) for Egypt, and Bodach (2014) for Nepal. Nijimeh and Baker, 2000 recommended passive design strategies for Amman, Jordan based on Givoni's BBCC. Similarly in Lebanon the charts were the bases for the Design Guide for Lebanon developed by UNDP (UNDP, 2005).

2.2.1.1 Lomas et al, 2004, Building bioclimatic charts for non-domestic buildings and passive downdraught evaporative cooling:

Using dynamic thermal simulation (ESP-r), Lomas et al. (2004), tested the validity of the direct evaporative cooling boundary, suggested by Givoni, for an office building located in Seville, Spain. Only the peak daily ambient dry bulb temperatures and corresponding wet bulb temperatures for the period June-September for Seville were plotted on the charts, suggesting that comfort would not be attained on 60% of days for buildings cooled by night-time ventilation alone. However, for a better insight, the hourly values of temperatures for the working hours of the day that fell outside the night comfort zone, were plotted. The analysis showed that up to 42% of these hours fell within the comfort zone. Then the hourly values were plotted against the direct evaporative cooling boundary. The results suggested that thermal comfort could be attained by direct evaporative cooling for 72-76% of the time. Then, the authors, using ESP-r, modelled an office building in Seville, a simple occupied office space, passively cooled by direct evaporative cooling, to check the validity of the BBCC results. Two construction types, light and heavy weight, and three different levels of internal gains, were modelled. The simulation results demonstrated that Givoni's boundaries were unreliable for non-domestic buildings as shown in Figure 2.2.

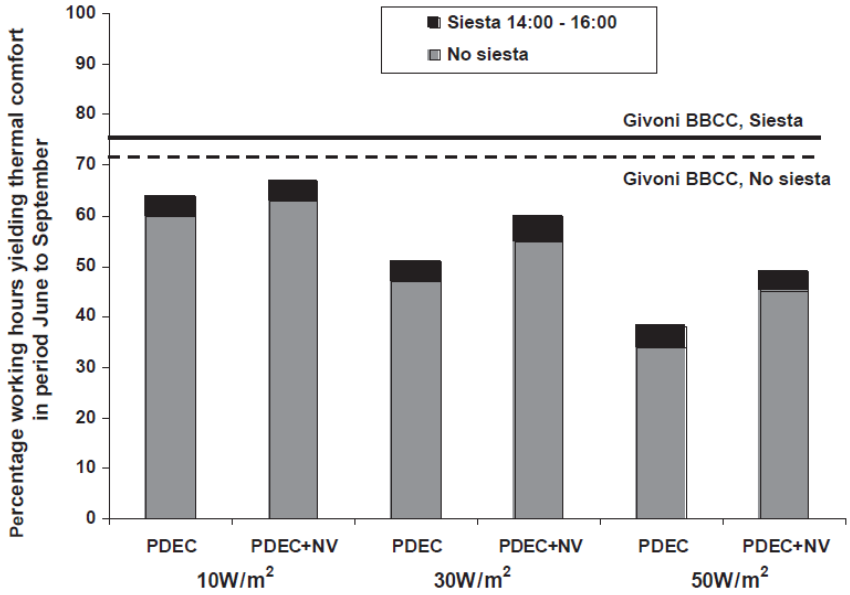


Figure 2.2: ESP-r modelling results of an office building with direct evaporative cooling and with or without natural ventilation for different internal gains levels as compared to Givoni's BBCC, (Lomas et al., 2004).

However, it could be argued that the percentage of time in which comfort could be achieved by direct evaporative cooling, as established by the BBCC, was only slightly higher than that obtained by ESP-r modelling, by Lomas et a., for the scenario with low internal and solar gains (10W/m^2). This suggested that the BBCC predictions are valid for domestic buildings where such low internal gains could be found.

The study proposed new boundaries for direct evaporative cooling in office buildings for the chosen climate, taking into account different levels of internal heat gains. It suggested two boundary lines; one that defined the upper limit of climatic conditions, above which comfort could not be achieved, irrespective of the internal heat gains, and another defined the lower limit of climatic conditions within which there was a risk of discomfort depending on the building conditions, Figure 2.3.

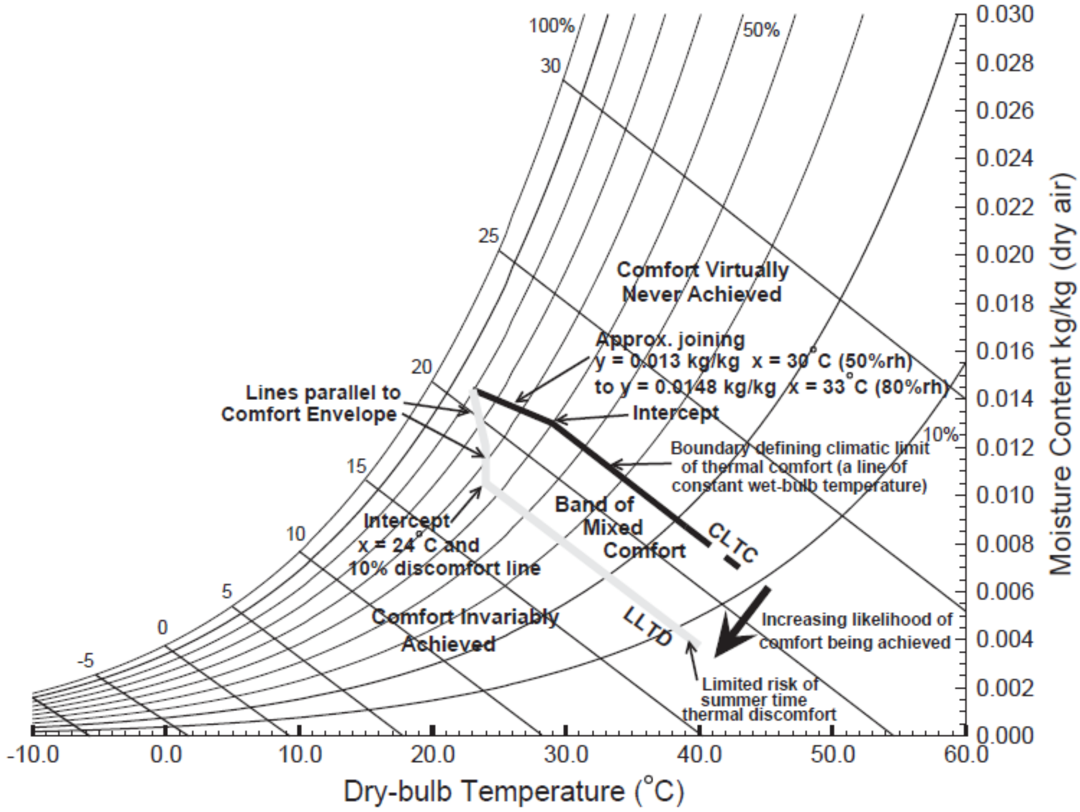


Figure 2.3: Features of proposed BBCC's based on thermal simulation of an office building in the Seville climate (Lomas et al., 2004).

2.2.1.2 Visitask 2007, an evaluation of the bioclimatic chart for choosing design strategies for a thermostatically-controlled residence in selected climates (PhD theses):

This study investigated the applicability of using the Givoni-Milne bioclimatic chart (1979) for a single-family house with a Heating Ventilation Air Conditioning (HVAC) system in six different climates. The six selected climates and their representative cities in this research were:

1) Very hot-humid (Bangkok, Thailand),
2) Hot-humid (Houston, Texas),
3) Hot-dry (Phoenix, Arizona),
4) Warm-marine (San-Francisco, California),
5) Cool-humid (Chicago, Illinois, Boston, Massachusetts), and,
6) Cool-dry (Boise, Idaho).

The design strategies, that were investigated in this study included:

1) Lightweight house (base case),

2) Lightweight house without internal loads,

3) High thermal mass house, and,

4) Lightweight house with an economizer.

A typical single-family house was selected and modelled with DOE-2 (DOE-2, 2013). The ASHRAE-55-1992 comfort zone was used to evaluate indoor comfort conditions. New boundaries were suggested for a thermostatically controlled one-story house in hot and humid climates as shown in Figure 2.4. Discrepancies were noted between the new suggested boundaries and the Givoni-Milne boundaries.

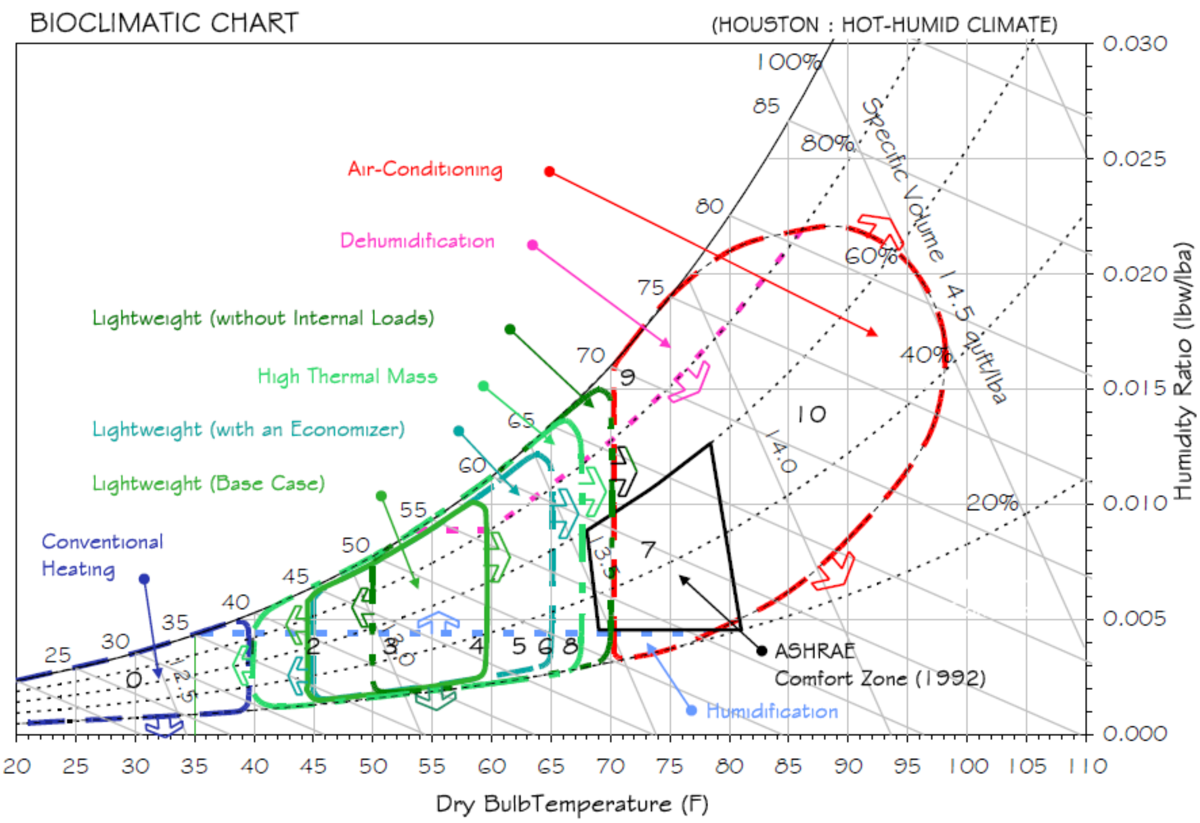


Figure 2.4: the bioclimatic chart for thermostatically controlled residences in hot-humid climate (Visitask, 2007).

The study by Visitask exhibits deficiencies in two main areas. The first is the failure to acknowledge the degree of applicability that the case study dwelling (with HVAC system) has to the passive design building typology intended for the Givoni-Milne chart. The Visitask HVAC building will have a narrower comfort zone in comparison with that associated with a passive design.

The second is in the conclusions the author draws, illustrated by the above figure 2.2. The zone proposed to signify a need for air conditioning appears to overlap the suggested comfort zone.

2.2.1.3 Roriz 2006, ABC software (Architectural Bioclimatic Classification):

Architectural Bioclimatic classification (ABC) is software developed by Roriz (2006), based on Givoni's charts, it uses hourly temperatures and humidity values generated using an algorithm developed by Roriz. Mean monthly minimum and maximum dry bulb temperatures and mean monthly relative humidity were used to plot the percentage of comfort hours. The software includes a climatological database obtained from the BBC weather website and national Meteorology institute in Brazil. Figure 2.5.

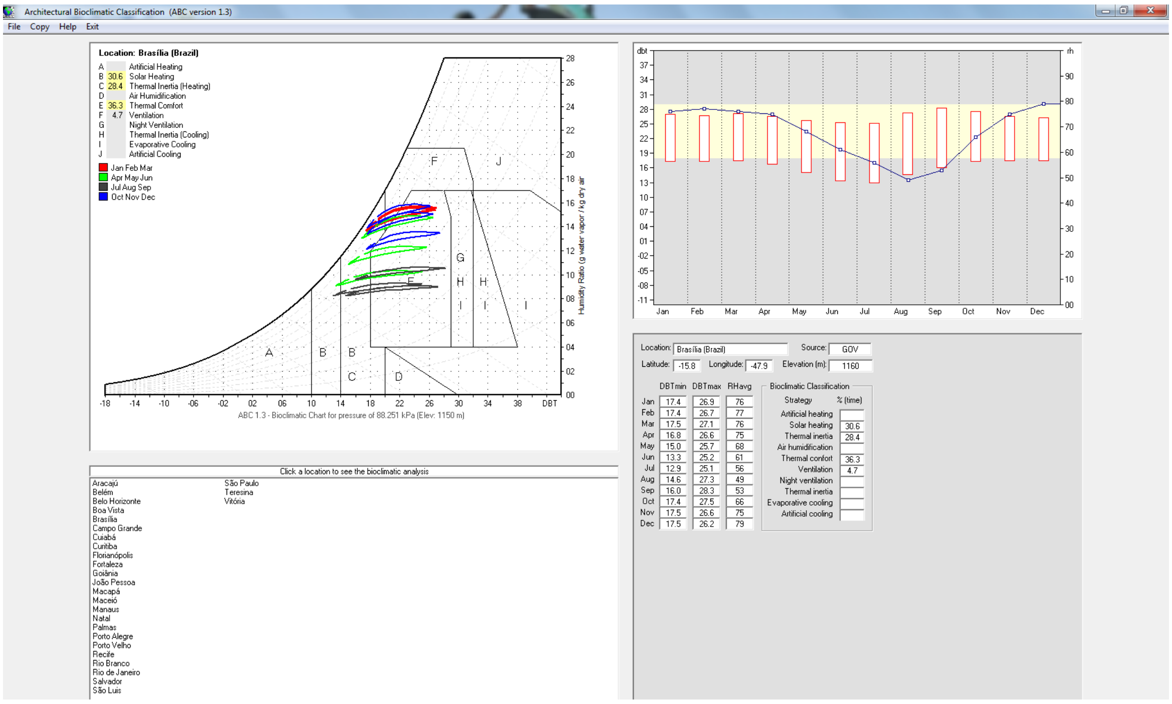


Figure 2.5: Screen shot of ABC software showing the percentage of time in which selected strategies can provide thermal comfort in Brasilia.

2.2.1.4 ZEBO a computer based energy tool:

ZEBO is a decision support tool for the study and design of net zero energy buildings, in hot climates during the early design phases. It was developed by Attia et al, (2011). The aim of this tool was to facilitate and integrate the use of energy building performance simulation for architects in hot climates. The tool was mainly used in Egypt by 20 architects, (DOE, 2013). The tool uses Givoni's comfort zones to thermal comfort criterion. The Givoni chart can be used prior to, or after design, to estimate the necessity of installing a building conditioning system. The chart can also estimate the impact of mechanically assisted ventilation using, e.g., ceiling fans with local wind speeds ranging from 0.5 to 2 m/s as a desirable strategy for unconditioned buildings in hot climates.

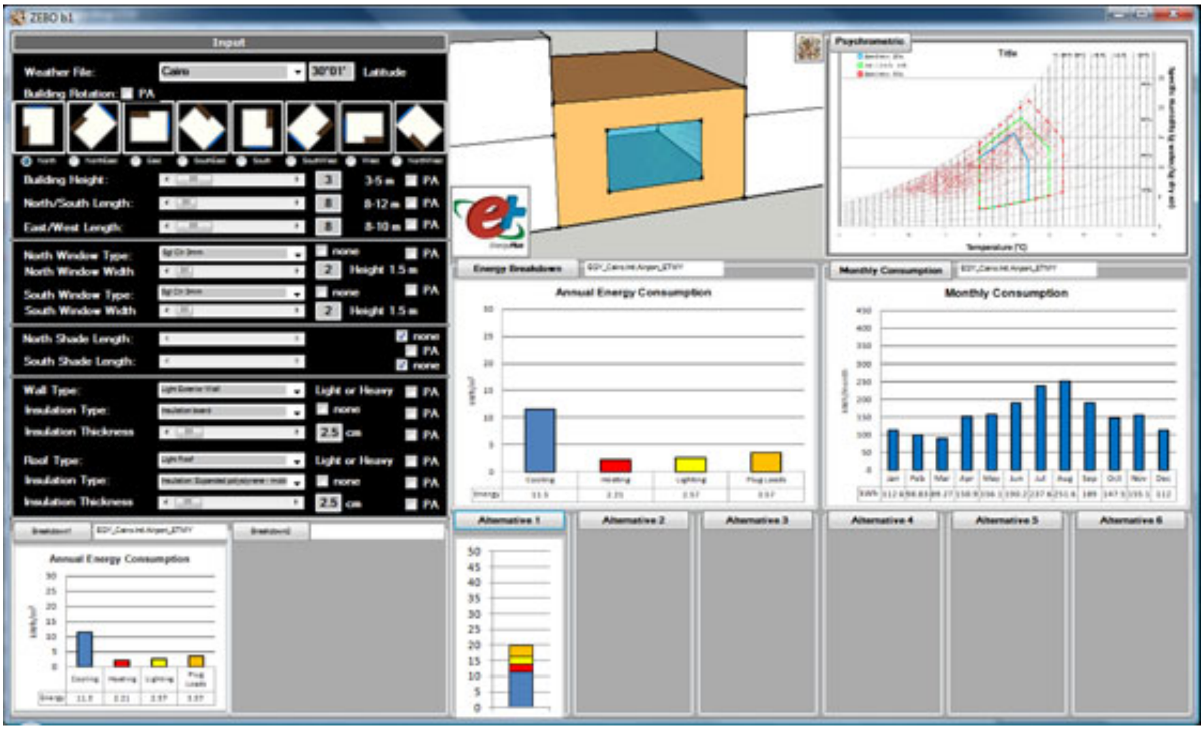


Figure 2.6: a screen shot of ZEBO (DOE, 2013).

2.2.2 Using the charts

The most common way of using the charts is by plotting monthly climatic line for each month. Monthly climatic lines are obtained by connecting two points on the psychometric chart, each point represent one end of the weather conditions (temperature and humidity) of a chosen month. The minimum mean DBT and the maximum mean RH (am) of a given month is plotted as one point, and the minimum mean RH (pm) and the maximum mean DBT of the same month as another point, by connecting the two points we can get the monthly climatic line for that month as shown in Figure 2.7a. Then the percentage of time that the monthly climatic lines falls within the boundary of a certain strategy may be determined, as shown in Figure 2.7b. This method was used, among others, by Bodach

(2014), Mahmoud (2011), Lam et al., (2006), Ajibola (2001), Sayigh and Marafia (1998), Zain Ahmed et al., (1998), Givoni (1992), and Al-Jamal and Sayigh (1988).

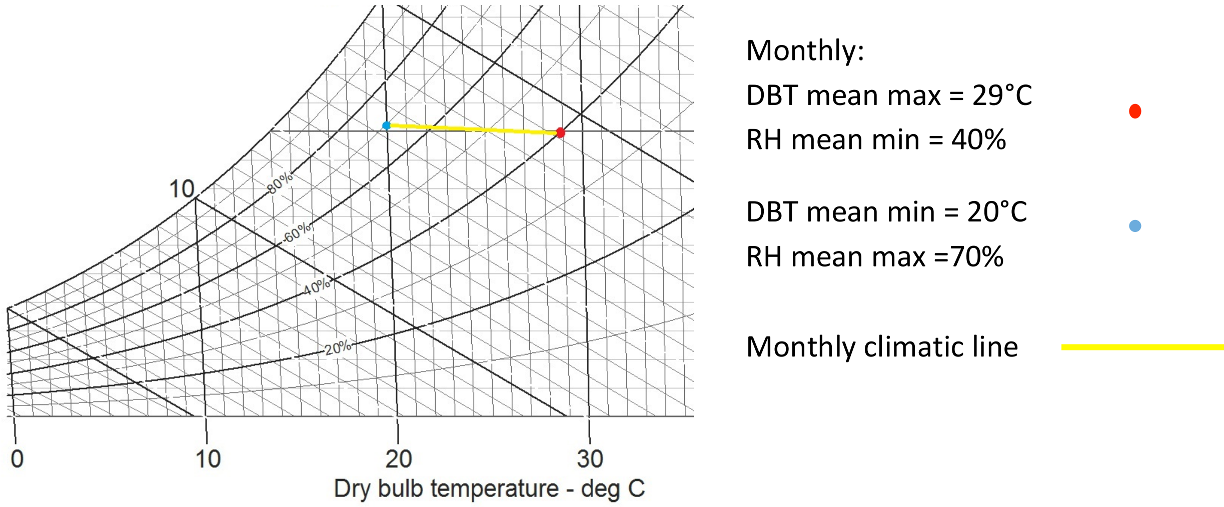


Figure 2.7a: Example of how to plot a monthly climatic line.

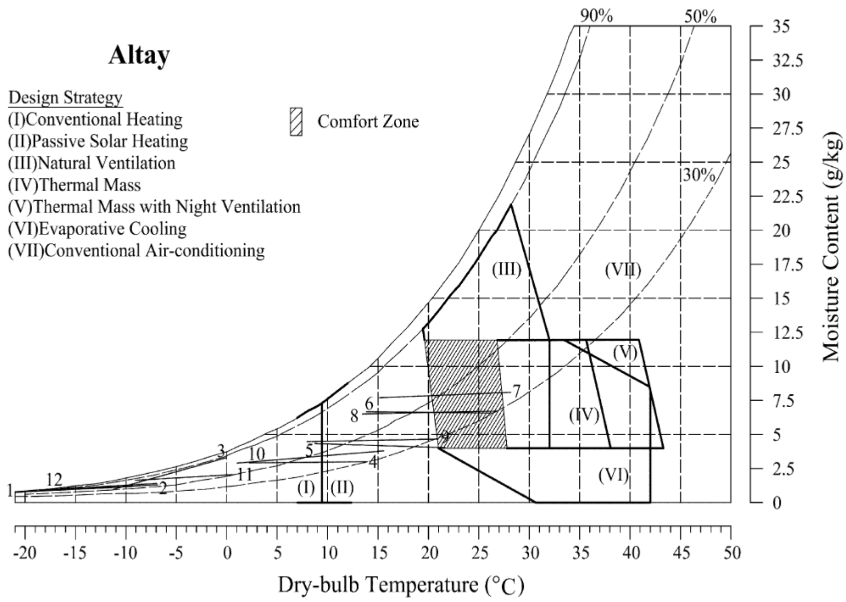
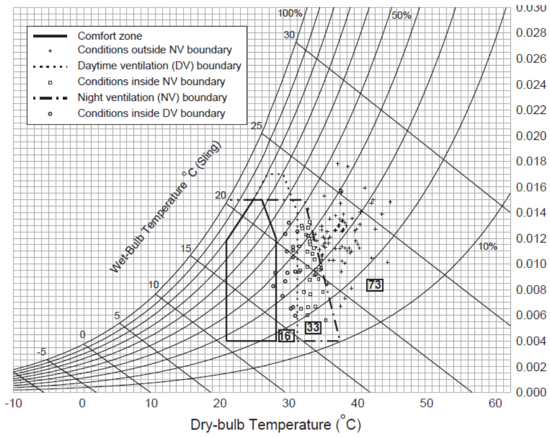


Figure 2.7b: Monthly climatic lines for Altay, China (Lam et al., 2006)

Another more complex method used by Lomas et al, (2004) is by plotting peak daily ambient DBT and the corresponding WBT, as in figure 2.8a. For a more in-depth analysis the hourly ambient conditions during occupied hours could be plotted as shown in figure 2.8b. However this level of analysis might become a practical difficulty for architects and inhibit them from using the charts, (Lomas et al 2004).



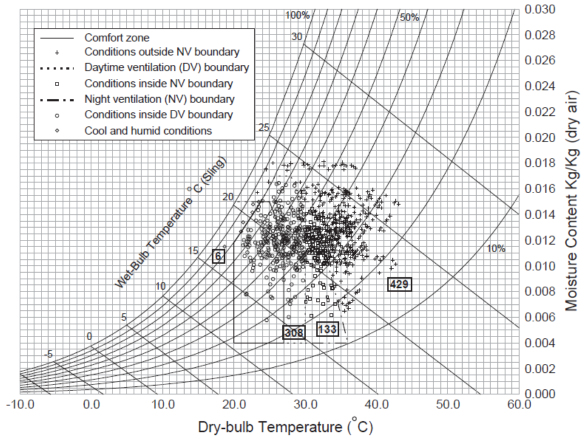


Figure 2.8a: Peak daily DBT and corresponding WBT for Seville (Lomas, et al 2004). Figure 2.8b: Hourly ambient conditions during working hours (Lomas et al, 2004).

2.3 Deficiencies of the BBCC: The thermal comfort zone

There is a question on whether the widely used method of plotting monthly climatic lines to assess the potential of certain strategies is a viable method; the average monthly conditions represented by the climatic lines may not necessarily reflect the real potential of a strategy. Alternatively, manually plotting hourly weather conditions can be a deterrent for using the charts. Additionally, the charts assume a “well-designed” building that is high thermal mass, good thermal resistance and minimum solar gains. To what extent varying these parameters will affect the position of the charts isn’t known.

Most importantly, Givoni suggested two different comfort envelopes, one for developed and another for developing countries, as mentioned in the preceding paragraphs. This was because the ASHRAE Standards-55, (ASHRAE, 1992), and the Fanger comfort formula, (Fanger, 1973), did not consider personal acclimatization and therefore they were less suited for use in un-conditioned buildings in hotter climates, (Givoni, 1992). He also argued that popular expectations of comfort and standards of living were not usually considered and therefore, “it is basically impossible to have universal comfort indices and standards”, (Givoni, 1992). He also stated, “it is reasonable to assume that people in *developing* hot countries, living mostly in non-air-conditioned buildings, were acclimatized to, and would tolerate, higher temperatures and/or humidity”, thus he suggested an elevation of 2°C and 2 gr/kg moisture content for developing countries. Two points need to be discussed here, acclimatization and expectations based on standards-of-living.

2.3.1 Acclimatization

Givoni's contention regarding the acclimatization of the population in hot climates is reinforced in recent literature. Many researchers have demonstrated that people living in hot climates are satisfied at temperatures as high as 30°C or more, which were deemed uncomfortable, (Nicol, 1993; De Dear, 1998; and Humphreys and Nicol, 1979 & 2002; Baker and Standeven, 1996). As a result, the Adaptive approach to thermal comfort gained more credibility over the steady state temperature approach and in particular the predicted mean vote (PMV) index for un-conditioned buildings.

The steady state approach was the result of Fanger's studies (1973) in a climate chamber that showed that the thermally comfortable zone was the same throughout the day and the year, and that no differences in comfort conditions existed in winter and summer, therefore the thermally comfortable zone should be maintained throughout the day/season. This was known as the rational approach to thermal comfort using the predicted mean vote, and resulted in a narrow thermal comfort zone. Heschong (1979) explained that the reason behind the steady state approach was that it assumed any degree of thermal stress was undesirable, and any effort made in order to adjust to the thermal environment should be avoided and therefore, a constant temperature be maintained. On the other hand, Humphreys and Nicol (1972 & 2002) and other previously mentioned researchers introduced a new adaptive approach for thermal comfort based on field studies. This approach believes that people are acclimatised to, and are able to adapt to a wider range of temperatures and changes in thermal conditions in their environment. The adaptive theory considers physiological (acclimatisation), behavioural (adjustment) and psychological adaptation, (habituation and expectation).

2.3.2 Standards of living expectations

Expectations regarding standards of living could fall under psychological adaptation, which, according to De Dear et al. (1997) although the least studied is, in effect, the most significant factor that influences the individual's thermal experience. De Dear et al (1997) elucidated, "Psychological adaptation encompasses the effects of cognitive and cultural variables, and describes the extent to which habituation and expectation alter thermal perceptions". The brain's interpretation of warmth or coldness as pleasing or displeasing is influenced by the psychological conditions against which the stimuli are received, such as the individual's recent thermal history, age, sex, culture and expectations, (Nicol, et al., 2012). Supported by other studies De Dear et al (1997) concluded that different responses were obtained in different indoor environments such as the home, office, in conditioned or naturally ventilated buildings, due to psychological adaptation. However, there is insufficient evidence to suggest that people in *hot developing* countries are more comfortable at higher temperatures than those experienced by people in *hot developed* countries. Most of the studies that looked at psychological adaptation did not associate the country’s economic classification with the population’s comfort expectations. Psychological adaptation seems to include many variables that are not all studied as extensively or supported by field studies. Recent research seems to focus more on the relationship between psychological factors such as, the access to controls, and the sensation of thermal comfort; or the distinction between thermal perceptions in naturally ventilated buildings, versus air-conditioned based on occupants' expectations.

Few studies have investigated the relation between subjects’ economic classification and their thermal sensation. A study by Han et al., (2009), looked at rural and urban thermal comfort in naturally ventilated residential buildings in winter, and found that the mean thermal sensation vote of rural residences was approximately 0.4 higher than that of urban residences at the same operative temperature, suggesting that rural occupants may have had a higher tolerance or lower expectations. Karyono et al., (2014) conducted a thermal comfort study in two private universities that had significantly different tuition fees in Jakarta. 100% of the students surveyed in the first university had air-conditioning units in their accommodation, while only 50% of the students in the second university had the same. The results found that the comfort temperature of the second group was 0.8K higher than the first group. Indraganti and Rao (2010) found that the mean overall comfort temperature was always higher in lower economic groups, (Table 2.1). In addition, a greater tendency towards non-adaptive behaviour and lifestyle was found in the higher economic groups (Group-1, 2).

Table 2.1: Group-wise regression analysis of Indoor Globe Temperature (Tg) and Thermal sensation for neutral temperature (all data). Lower economic groups (group-3) have a higher neutral temperature and a much higher comfort band, (Indraganti & Rao, 2010).

Economic group	Correlation coefficient, r	Regression slope	Constant	Neutral temperature Tn (°C)	Comfort band - lower limit	Comfort band - upper limit
GROUP-1	0.51	0.298	8.451	28.4	25.0	31.7
GROUP-2	0.72	0.325	9.499	29.2	26.2	32.3
GROUP-3	0.75	0.344	10.39	30.2	27.3	33.1
ALL DATA	0.65	0.31	9.06	29.2	26.0	32.5

It should be noticed that there is a strong correlation r= 0.75, r=0.72 between the thermal sensation and the indoor globe temperature in lower economic groups; group-3 and group-2 respectively. This was explained by the author by reduced usage of air-conditioning in the lower economic groups. Subjects of group-1 preferred much lower temperatures even though their indoor temperatures were the lowest, revealing a low level of tolerance.

These studies compared the thermal sensations of different economic classes within the same country, but no study was found that compared the comfort vote between populations of developed and developing countries. The ASHRAE project RP-884, which includes adaptive thermal studies from all over the world covering a wide range of climatic zones, did not distinguish between the expectations of the population based on their national economic classification in its final report, (De Dear et al., 1997), and its new adaptive standards, (ASHRAE, 2004, 2010 & 2013). The ASHRAE project covered a wide range of hot, cold and temperate climates. However, only two projects out of twenty in the ASHRAE project were conducted in hot developing countries, namely, Indonesia, (Karyono, 1996), and Pakistan, (Nicol et al., 1994), Figure 2.9.

Figure 2.9: ASHRAE project RP 884 1995-1997, the red dots shows the regions where thermal comfort surveys were conducted.

In this research the ASHRAE database was revisited to assess whether a comparison between the comfort vote of developed and developing countries (with a hot dry climate) could be done. There were no studies on naturally ventilated buildings in developed countries with hot arid climate similar to Pakistan (a developing country); the studied buildings in the Australian desert were HVAC buildings. Indonesia (a developing country) and Singapore (a developed country) both have a wet equatorial climate; the studies conducted in these two countries naturally ventilated buildings, so this thesis examined these countries more closely to investigate the influence of country's development on the neutral temperature in naturally ventilated buildings.

De dear et al., (1991) study found that the neutral operative temperature was 28.5°C for naturally ventilated buildings in Singapore. Karyono (2000) comfort survey in Indonesia reported a neutral temperature of 26.7°C. It did not distinguish between the neutral operative temperatures for occupants surveyed in air-conditioned buildings and naturally ventilated buildings; the figure represented a sample of both building typologies combined.

By downloading the raw data of both surveys from ASHRAE RP-884 adaptive model project - data downloader (ASHRAE RP-884, 2014), it was found that the sample size surveyed was significantly different in the naturally ventilated buildings in the two countries. Ninety-two occupants were surveyed in the naturally ventilated building in Indonesia over one week, while 583 occupants were surveyed in the naturally ventilated building in Singapore over two weeks. Linear regression analysis of the Singapore survey data in naturally ventilated buildings (See Figure 2.10) concluded the same neutral temperature for Singapore as that reported in De dear et al., (1991).

On the other hand, by extracting only the data associated with naturally ventilated buildings only in Indonesia, regression analysis found the neutral temperature to be 26.5°C (Figure 2.11). This meant that the neutral temperature in the developing country was lower than the developed one. This is contradictory to Givoni's contention that people in hot developing countries are comfortable at higher neutral temperatures than hot developed ones. However, it should be noted that linear regression may not suitable to calculate neutral temperature for Indonesia study, because all 92 occupants' responses were on the warm side of the scale, and the extrapolation entailed resulted in very poor correlation.

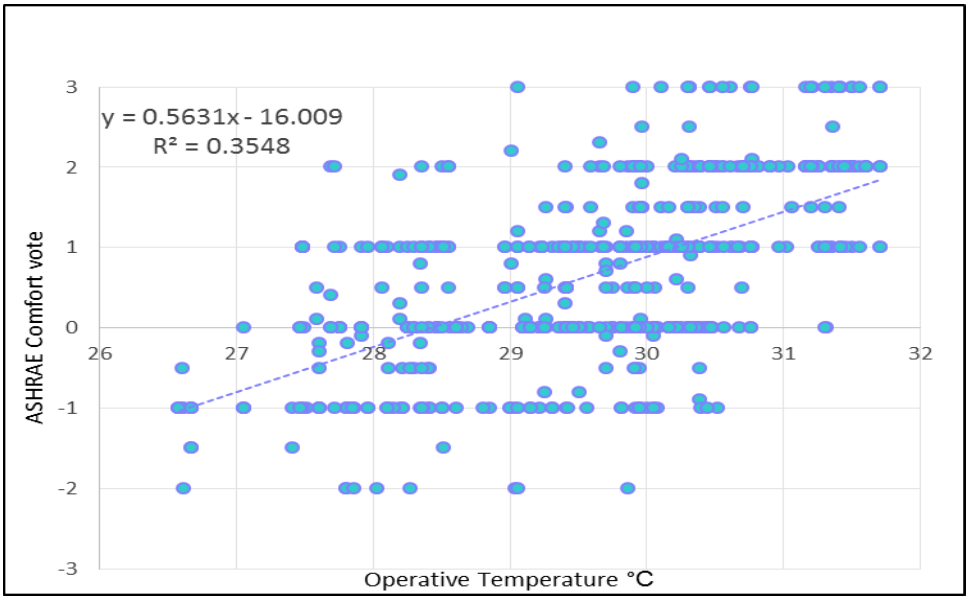


Figure 2.10: Regression line of comfort vote on operative temperature in Singapore

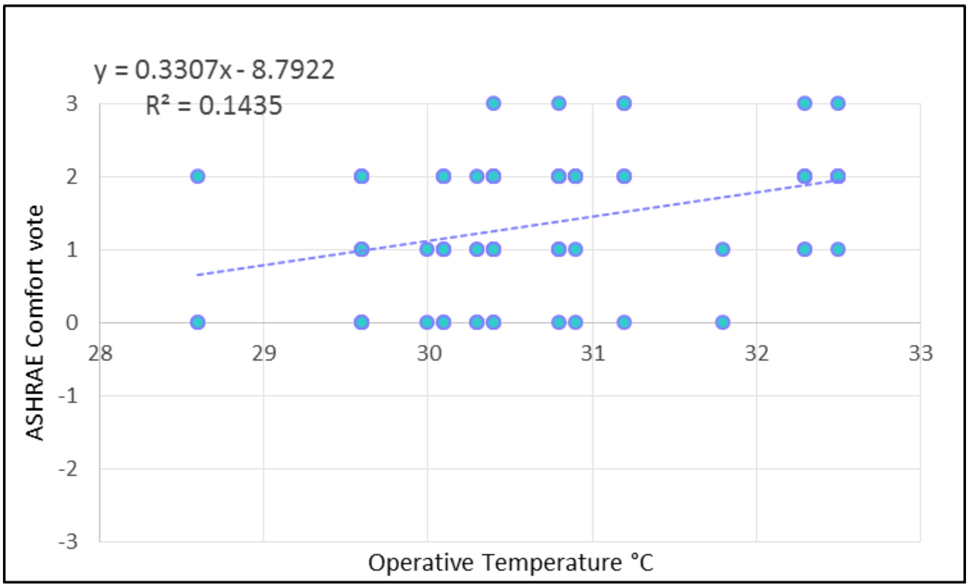


Figure 2.11: Regression line of comfort vote on operative temperature in Indonesia

Revisiting ASHRAE database did not support Givoni's argument. Therefore, the suggested increase in the comfort range for populations of developing countries, as in Givoni's comfort zones, is questionable. Also it should be considered that within any country, whether it was developed or developing, different economic groups will be found. Additionally, the concept of **tolerance**, **acceptance** and **preference** is different; in other words, people with limited financial sources may tolerate and accept higher temperatures but this does not necessarily mean that they would prefer it. Indraganti (2010) explained that "thermal acceptance" is a different concept from "thermal comfort". In a study on thermal comfort in India, the author found that although only 8% voted neutral on the sensation scale in May, 69% of the subjects voted that the thermal environment was acceptable on the acceptance scale, Figure 2.12.

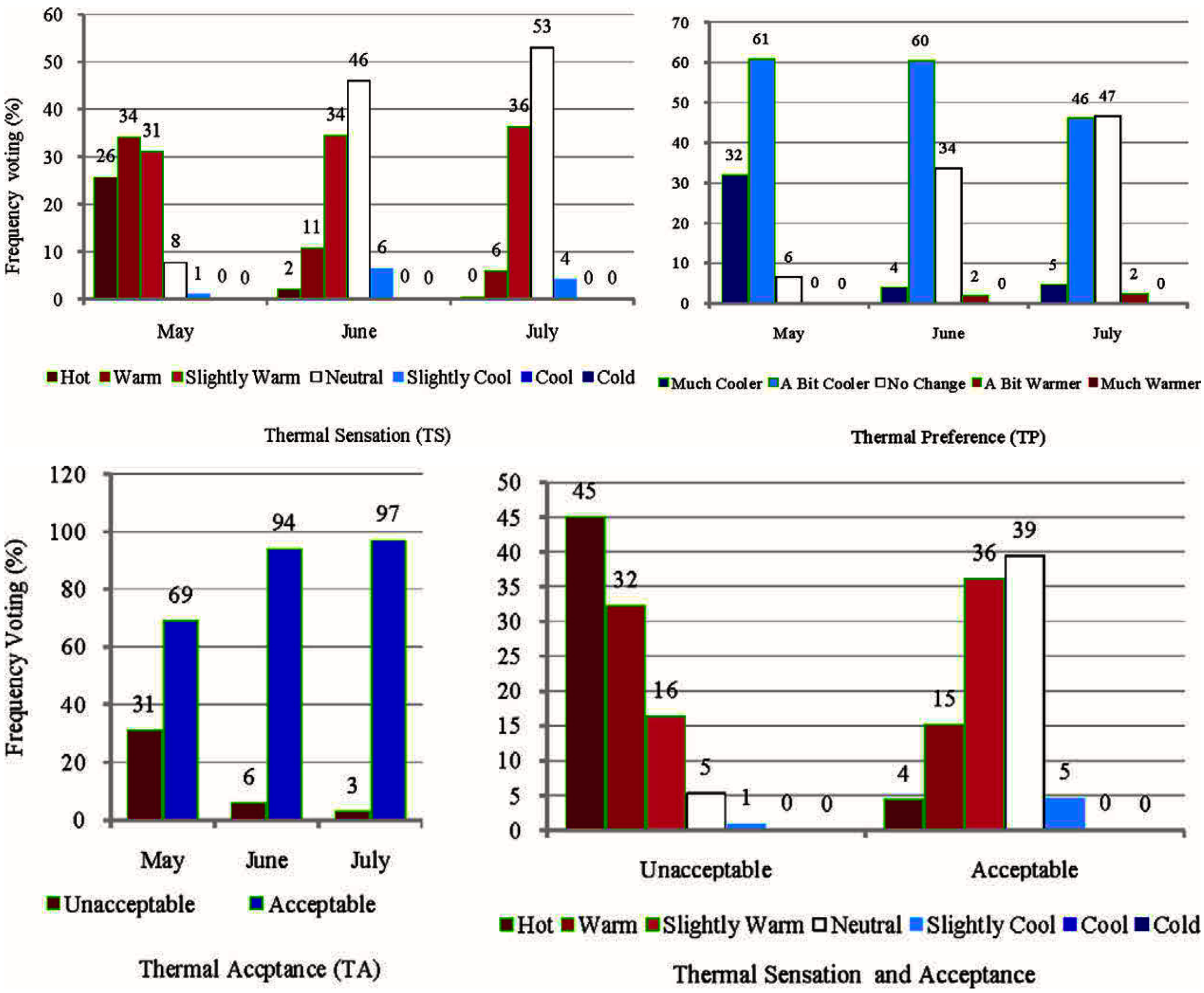


Figure 2.12: (Indraganti, 2010) thermal sensation, preference and acceptance.

2.3.3 Comfort envelopes in current international standards

Mainly, there are two internationally recognised thermal comfort standards, the ASHARAE Standards, and the European Standard EN15251, which have incorporated an adaptive component in their most recent versions, whereas ISO 7730 is still based on the PMV index.

2.3.3.1 ASHRAE standards 55-2004/2010

The new ASHRAE standard 55-2004, and more recently 55-2013, incorporates the adaptive theory for naturally ventilated buildings, following ASHRAE, project RP884 1995-1997. It provides data collected from 160 buildings across the world. The RP-884 project concluded with two variable temperature Standards. The first Standard was designed for use in HVAC buildings where occupants had little or no adaptive opportunity, while the second was designed for naturally ventilated buildings where occupants had access to operable windows and other adaptive opportunities such as, changing clothes. Two zones were defined for naturally ventilated buildings, one for 80% acceptability and another for 90% acceptability, derived from the formula:

$$T_{comf} = 0.31T_o + 17.8 \qquad (1)$$

Where T_o is the prevailing mean outdoor temperature[2] however when daily mean temperatures aren't available to calculate the prevailing mean temperature, the mean monthly temperature could be used.

The ASHRAE standards could be considered as the only truly international Standard as the comfort envelopes were derived from research conducted in both developed and developing countries.

2.3.3.2 European Standard EN15251

Similarly, to ASHRAE, EN15251 also provides standards for two building options, one for mechanically cooled buildings based on the PMV and another for free-running buildings based on the adaptive theory. The EN15251 uses its own database collected in five European countries in the SCATs project (Smart Controls and Thermal Comfort). The comfort equation used was:

$$T_{comf} = 0.33T_{rm} + 18.8 \qquad (2)$$

Where T_{rm} is the exponentially running mean of the outdoor temperature[3].

2.3.3.3 Humidity and the adaptive model

In both adaptive Standards' comfort zones, the effect of humidity is overlooked. Nicol et al. (2012), note that there wouldn't be any difficulty in including the effects of humidity and air speed in the adaptive model. In order to address the effect of humidity, Nicol (2004), revisited three databases to look at the effect of humidity on thermal comfort. These databases were; the ASHRAE 1998, Humphreys 1975, and the Pakistan project, (Nicol et al., 1999). He concluded that in climates where relative humidity is very high (RH>75%), people might require temperatures that were 1°C lower than conditions where RH is lower RH<64%.

[2-3] The prevailing mean temperature and the running mean temperature describe temperature change with time, it is a weighted mean that takes into account that temperatures in days closer to the day in question has higher impact on the adaptive comfort temperature than previous days

Additionally, in hot-humid climates the range of comfort temperatures is limited compared to hot-dry conditions, as humidity increases, the feeling of discomfort when outdoor temperatures are above 30°C, increases.

2.3.4 Other existing comfort envelopes and equations

Many comfort envelopes have been developed, mainly by Standards' developers to establish guidelines for the setting of HVAC systems in buildings. However, after the adaptive approach to thermal comfort gained more credibility, researchers looked at developing comfort envelopes that accounted for adaptive opportunities. Martinez et al. (2000) developed comfort envelopes for office buildings with a passive cooling system for summer conditions, Figure 2.13. The envelopes accounted for adaptive opportunities such as, changes in clothing, the use of local fans for enhanced air speed and the use of blinds for moderating/controlling unwanted solar radiation. The comfort envelopes were predicted using a detailed dynamic model of human heat transfer and thermal comfort developed previously by Fiala, (1998).

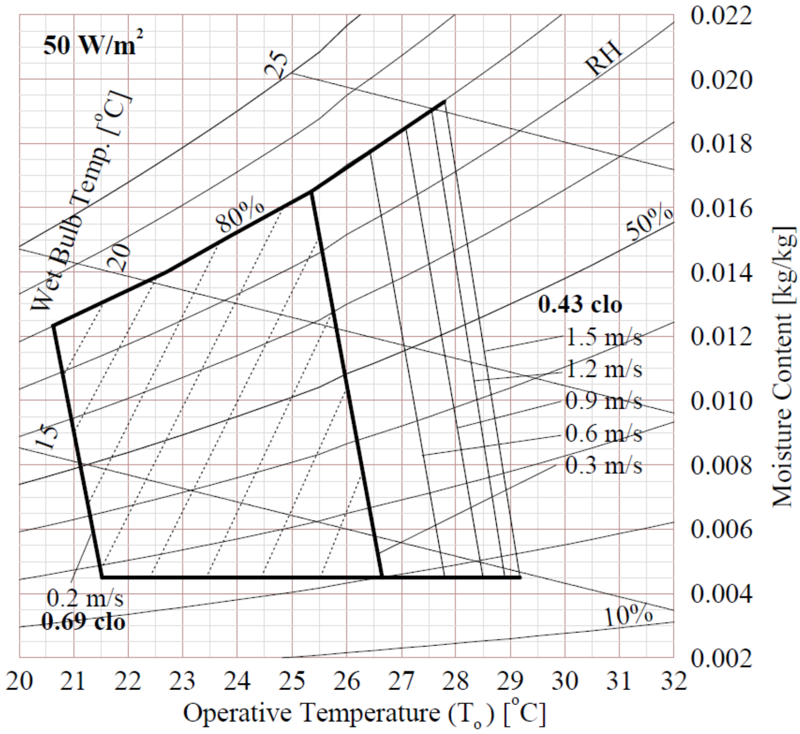


Figure 2.13: (Martinez et al. 2000) thermal comfort envelops for buildings with passive cooling system in warm conditions, with 50W/m2 heat gains.

Nicol et al, 2012 suggest using the following equation for comfort temperature based on analysis of ASHRAE data by Humphreys et al., 2010.

T_{comf}= 0.53(T_{om}) +13.8 (3)

T_{om} is the monthly mean outdoor temperature calculated from meteorological records of outdoor mean maximum and minimum temperatures.

Nicol et al., argue that there is still some question of whether ASHRAE equation (1) could be used irrespective of what measure of outdoor temperature is used. They suggest the use of equation (3) because monthly mean outdoor temperatures are widely available.

2.3.5 Thermal comfort envelopes in the developing world:

As shown previously, ASHRAE-55 is the only international Standard that was developed based on research conducted in both developed and developing countries. It is widely accepted that countries should develop their own comfort standards as the perception of comfort varies according to the local climate, culture and expectations, (Nicol, 2012; Bouden and Ghrab, 2004). Therefore, there are other individual thermal comfort studies conducted in a few developing countries such as, Iraq and India (Nicol, 1973), in sub-Saharan Africa, (Djongyang and Tchinda, 2010), in Libya, (Ealiwa et al., 2001), in Tunisia, (Bouden and Ghrab, 2005), and in Iran (Heidari and Sharples, 2002). Unfortunately, none exist for the countries addressed in this thesis.

2.4 Summary

It is now apparent that there is insufficient literature that compares thermal comfort in developed or developing countries. Moreover, the literature review found evidence that people from different economic groups in the same country might be comfortable at different neutral temperatures. This demonstrated that Givoni's suggested 2°C elevation in the comfort zone temperature for developing countries was unfounded. Additionally, more research was needed to assess thermal comfort in the developing world, and establish preferences, tolerance and acceptance boundaries.

Two authors had investigated the validity of Givoni's BBCCs, Lomas et al. (2004), for an office building and Visitsak (2007) for a house with HVAC system; the shortcomings of these studies were discussed. In addition, two computer-based versions of Givoni's BBCC were developed, the ABC software and ZEBO. However, in regard to ZEBO, Givoni's BBCCs were only one feature of the program, and it was a much more complex program than ABC.

It was apparent that little research had been done to validate the charts. As Lomas et al, (2006) elucidated, a number of BBCCs might be needed to cover a wide range of buildings types, climates, design strategies, and occupancy performance. Givoni's BBCC are limited as they were based on limited number of field experiments; however, dynamic building simulation tools offer the opportunity to test a wider range of variables.

2.5 Identified gaps in knowledge

1- There is a need for guidelines on passive design for architects in the developing countries of the Eastern Mediterranean.

2- More research is needed to assess thermal comfort in the developing world, and establish preferences, tolerance and acceptance boundaries.

3- Givoni's bioclimatic charts are widely used however an investigation into their validity is required. This is because:

    a. The suggested 2°C elevation in *comfort zone* temperature for developing countries wasn't supported by research.
    b. The boundaries of the suggested *passive strategies* for developing countries are based on Givoni's personal evaluation.
    c. The applicability of the BBCC across different climates and different building designs requires investigation.
    d. There is a question around the validity of the different methods available to use the charts i.e. the plotting of climatic lines or hourly data; and what discrepancies, if any, exist between these two methods.

Chapter 3: The Applicability of BBCC for the Eastern Mediterranean region

This chapter aims to assess the suitability of passive cooling strategies for the Eastern Mediterranean (EM) climate using Givoni's BBCC. However, to do so requires differentiation between the climatic conditions that exist across the region through bio-climatic zoning, to define thermal comfort boundaries that passive cooling design strategies seek to achieve.

3.1 Bioclimatic zoning:

Using Köppen-Geiger climate classification (Kottek et al., 2006), six distinct climatic zones are defined as illustrated in Figure 3.1.

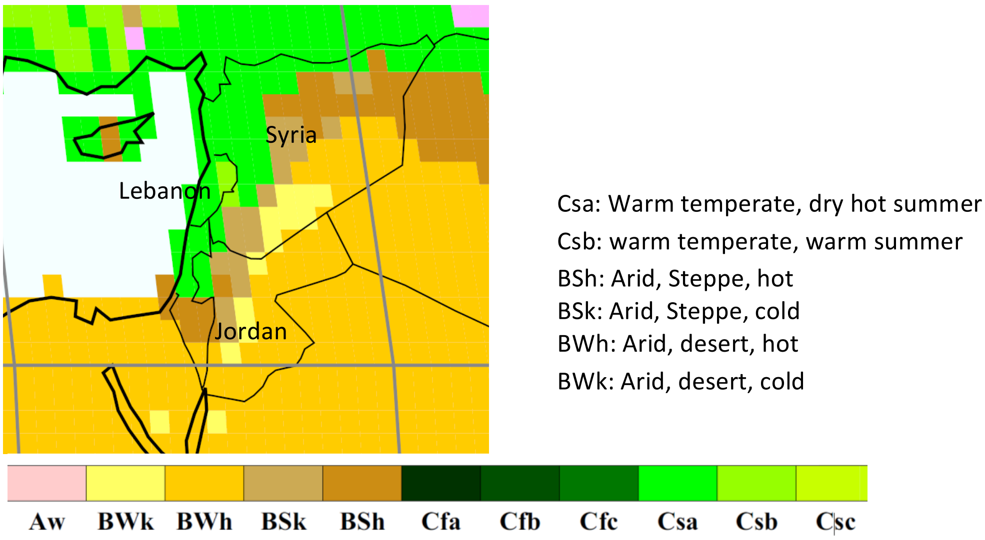


Figure 3.1: Köppen-Geiger climate classification for the Eastern Mediterranean region (Kottek et al., 2006)

Table 3.1: Köppen-Geiger climate classification for the Eastern Mediterranean region, where: T_{max} is the mean temperature of the hottest month, Tann the annual mean near-surface (2 m) temperatures, P_{ann} is the accumulated annual precipitation, P_{th} = 2 {T_{ann}}

CODE	GENERAL CLIMATE	DESCRIPTION
CSB	Warm temperate	Cold winters, warm dry summers: T_{max} <22◦C
CSA	Warm temperate	Rainy winters, hot dry summers: $T_{max} \geq$ +22◦C
BSH	Arid Steppe (hot)	T_{ann} > 18 °C, 5 P_{th} < P_{ann} < 10 P_{th}
BSK	Arid steppe (cold)	T_{ann} < 18 °C, 5 P_{th} < P_{ann} < 10 P_{th}
BWH	Arid desert	T_{ann} > 18 °C, $P_{ann} \leq$ 5 P_{th}
BWK	Arid desert	T_{ann} < 18 °C, $P_{ann} \leq$ 5 P_{th}

The Köppen-Geiger classification is the most widely used climatic classification, and the only one available for the EM region. It includes temperatures and precipitation levels but not humidity levels. A noticeable feature of the EM climate is the contrast between the warm temperate Mediterranean coast in the west and the hot arid desert in the east and south-east, creating a semi-arid region in between (The Library of Congress Country Studies, 2005). As shown in Table 3.1, BS and BW zones have the same temperature conditions but different precipitation. This means that a location in the Arid-steppe zone might have similar temperature and humidity levels to an Arid-desert zone but higher precipitation levels during winters. For the purpose of passive cooling building design and in order to establish a better understanding of the climatic diversity and design requirements of the region, a bio-climatic zoning that accounts to Relative humidity, instead of precipitation, was necessary. To do this, climatic information for 56 locations covering most inhabited areas of the Eastern Mediterranean basin was obtained from the FAO (food and agriculture organization of the United Nations) climatic tool Climwat (Fao, 2014). The climatic information included historic monthly mean maximum and minimum temperatures, monthly mean relative humidity, and monthly precipitation levels. This information was first categorised according to the Köppen-Geiger climate classification explained in Table 3.1. Doing so demonstrated that indeed two locations, falling in two different Koppen-Geiger zones, could in fact have similar mean monthly temperatures and humidity, with only precipitation levels differing. To illustrate this, the monthly mean temperature and humidity of the warm temperate zone only (Csa and Csb) were plotted on Figure 3.2. From the figure it could be noticed that the range of weather conditions experienced in each city varied considerably within this one Koppen zone. For example, Qamishli city and Jiser Al-Shghour had a mean temperature of the hottest month (T_{max}) higher 22◦C, dry summers and a winter precipitation level P > 370mm (440mm and 680mm respectively), making them fall in the same Climatic Koppen zone (Csa). However, T_{max} in Qamishli city was 32°C and mean RH below 30% while T_{max} of Jiser Al-Shghour 26°C and the RH about 50%.

The same is true for BS and BW zones, as illustrated in Figure 3.3. This meant that when precipitations levels were ignored and mean monthly temperature and mean relative humidity of the summer months were plotted, different climatic zoning could be achieved, as shown in Table 3.2 and 3.3.

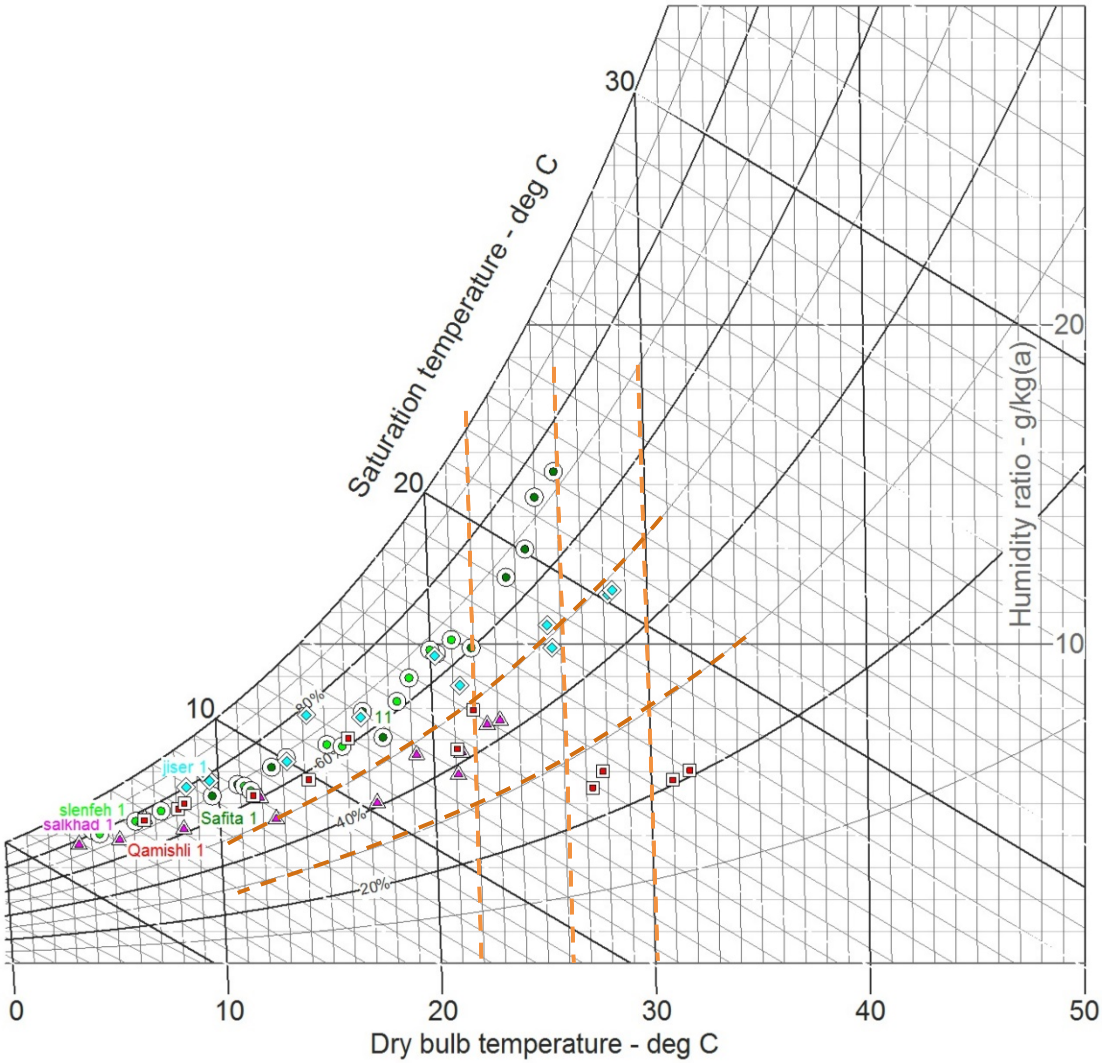


Figure 3.2: mean monthly weather conditions of five cities in the Koppen-Gieger warm temperate zone CSA and CSB.

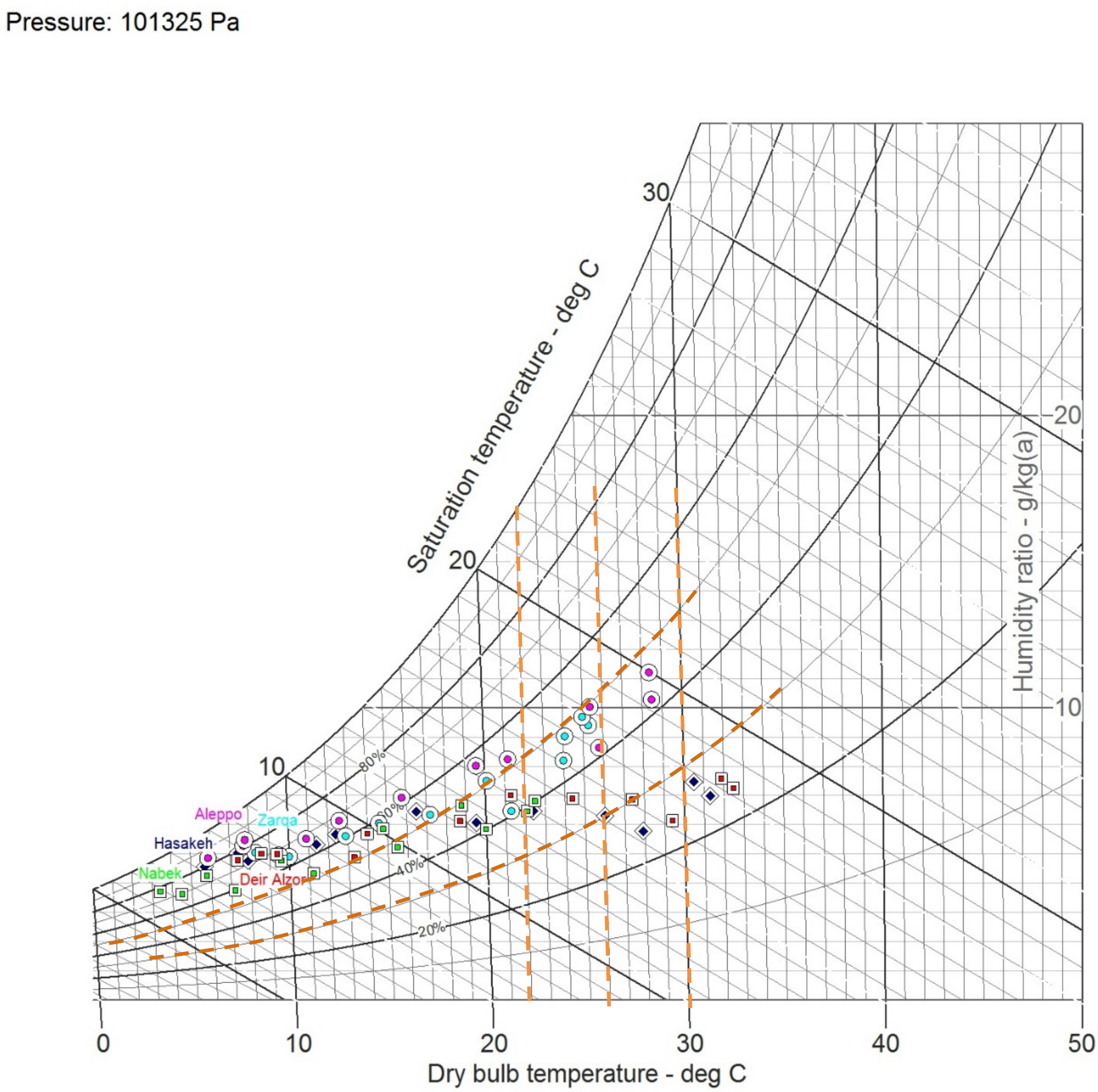


Figure 3.3: Mean monthly weather conditions of five cities in BS and BW zones

In order to categorize the available data from the 56 locations according to a new climatic zoning that takes into account humidity levels; mean monthly temperature of the hottest two months and their corresponding mean relative humidity were plotted, as shown in Figure 3.4. The figure is a Cartesian (x,y) plot, where the colour of the points represents the proposed zoning. This established six distinct climatic zones that extend across the EM, the conditions for each zone and a new climatic map are shown in Figure 3.5.

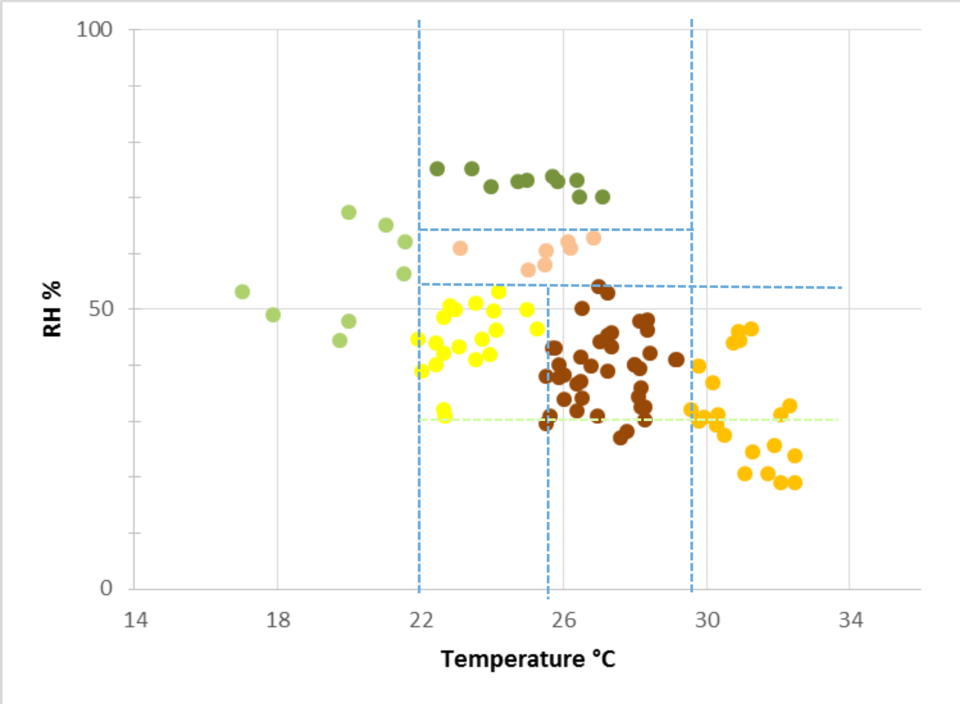


Figure 3.4: Mean monthly weather conditions of the hottest two months for 56 locations

Table 3.2: Suggested new bioclimatic zones for the cities illustrated in Figure 3.2 where T_{max} is the mean temperature of the hottest months and RHs is the relative humidity of summer months

SUGGESTED BIOCLIMATIC ZONE	CONDITIONS	CITY (KOPPEN ZONE)
COOL HUMID	T_{max} < 22°C RH_S > 55%	Slenfeh (CSB)
HOT HUMID	T_{max} > 22°C RH_S > 55%	Safita (CSA)
WARM DRY	25.5 <T_{max}< 29.5°C RH_S < 55%	Salkhad (CSA)
HOT DRY	25.5 <T_{max}< 29.5°C RH_S < 55%	Jiser al-shghour (CSA)
VERY HOT AND DRY	T_{max} > 30°C RH_S < 55%	Qamishli (CSA)

Table 3.3: Suggested new bioclimatic zones for the cities illustrated in Figure 3.3

SUGGESTED BIOCLIMATIC ZONE	CONDITIONS	CITY	KOPPEN ZONE
WARM DRY	25.5 <T_{max}< 29.5°C RH_S < 55%	Zarqa, Nabek	BSk BWk
HOT DRY	25.5 <T_{max}< 29.5°C RH_S < 55%	Aleppo	BSk
VERY HOT AND DRY	T_{max} > 30°C RH_S < 55%	Hasakeh Dier Alzor	BSh BWh

The six distinct climatic zones established are:

- A cool humid zone, where the monthly mean temperature of the hottest is lower than 22°C
- A hot humid zone, where the monthly mean temperature of the hottest month is higher than 22°C, and the mean summer relative humidity is higher than 65%
- A warm dry zone, where the monthly mean temperature of the hottest month is between 22°C and 25.5°C, and the mean relative humidity is below 55%
- A hot dry zone, where the monthly mean temperature of the hottest month is between 25.5°C and 29.5°C, and the summer mean relative humidity is below 55%
- A very hot dry zone, where the monthly mean temperature of the hottest month is higher than 29.5°C, and the mean relative humidity is mostly much lower than 55%
- A narrow region exist between the hot humid and the hot dry area where summer mean temperature of the hottest month is higher than 22°C, and its relative humidity levels are moderate between 55% to 65%

This zoning was considerate to the geographic location of each of the 56 cities and towns plotted in Figure 3.4. I.e. clumping of data evident on the graph was checked against a geographical plot of the locations, as shown in Figure 3.5. The zoning was also considerate of other factors influencing environmental design such as the diurnal range and the mean *maximum* temperature. For example, locations in the hot dry and very hot and dry zones had a diurnal range of more than 15K but monthly mean maximum temperature less than 33°C and higher than 38°C, respectively. On the other hand locations in the hot humid zone had a diurnal range less than 10K.

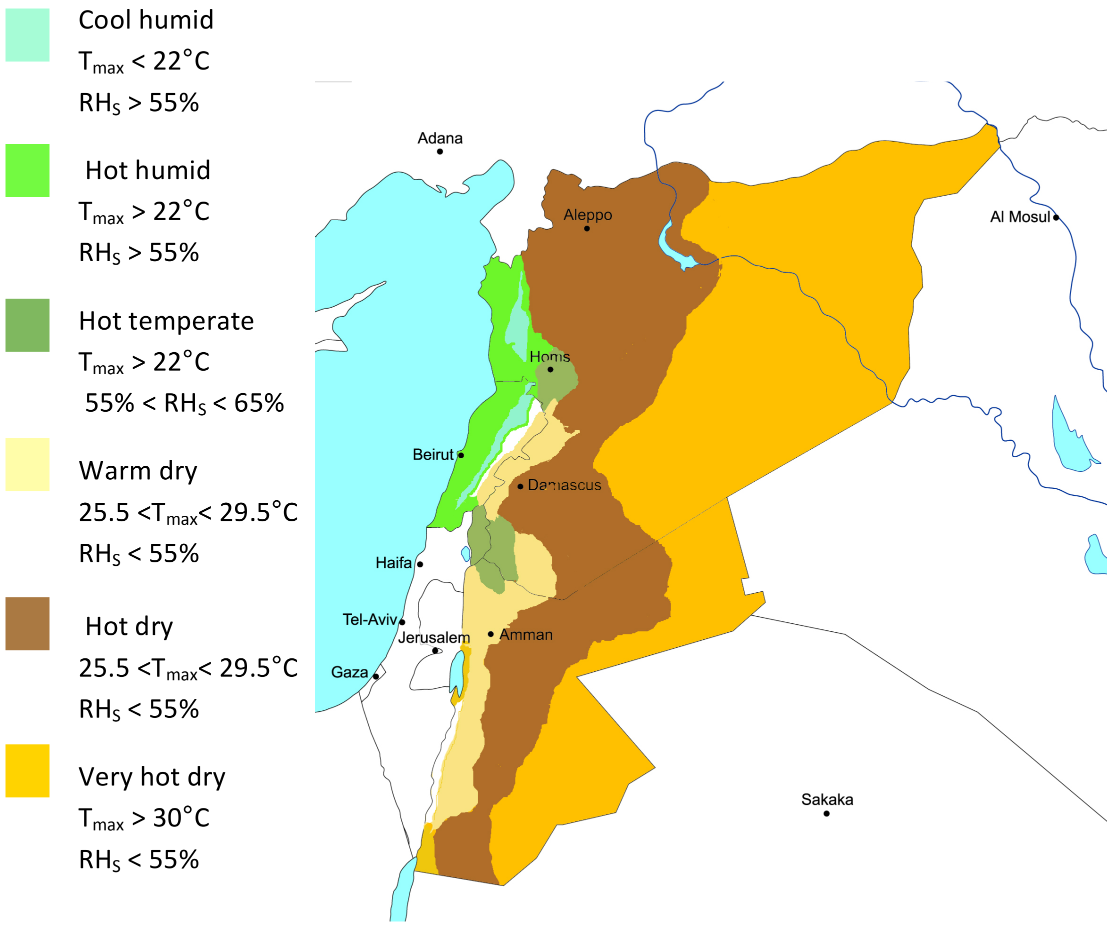


Figure 3.5: bioclimatic map for the EM developing countries. The borders of each climatic zone are indicative only and they generally follow topographic lines

3.2 The potential of passive cooling strategies using BCCC

The potential of passive cooling strategies according to Givoni's BBCC was assessed in the four dominant climatic zones, namely; the hot humid, the warm dry, the hot dry and the very hot dry zone. In later Chapters these predictions are compared with actual building performance in the region through building modelling and monitoring. As explained in Chapter 2, plotting monthly climatic lines on the BBCC to assess the potential of strategy is the most commonly used method. Therefore, monthly climatic lines for the cooling season of representative cities were plotted on the charts and the percentage of time in which comfort cannot be achieved by a strategy was calculated, Figures 3.6 to 3.9. Following that, and in order to test the validity of this approach, Lomas et al., (2004) method of plotting the hourly ambient DBT and the corresponding moisture content from available weather files[1]

[1] Refer to Chapter 5 for the choice of weather files used.

on the BBCC was used for Aqaba, Beirut and Damascus and the number of hours falling outside the DTV and NTV boundaries were calculated, Figures 3.10 to 3.12.

3.2.1 Monthly climatic lines:

Beirut

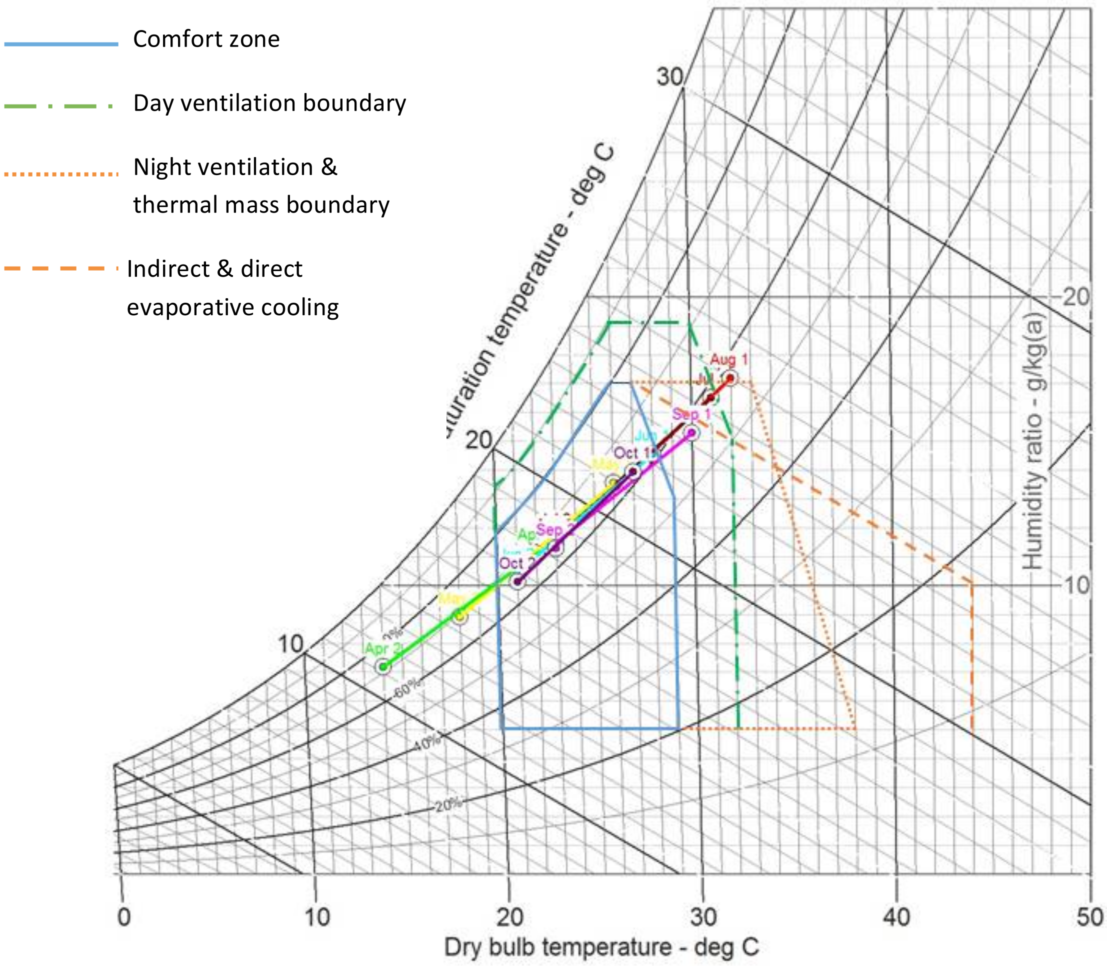


Figure 3.6: BBCC for Beirut city as a representative of the hot humid zone-each data point represent the extreme conditions at either end in a month

Table 3.4: Passive cooling strategies potential according to Figure 3.6; the table below shows for what percentage of the time comfort *cannot* be achieved (overheating), hot humid zone.

STRATEGY	APRIL	MAY	JUN	JUL	AUG	SEP	OCT
Day vent	N/A[2]	N/A	N/A	0%	11%	0%	N/A
Night vent	N/A	N/A	N/A	0%	2%	0%	N/A
Evaporative cooling	N/A	N/A	N/A	15%	27%	0%	N/A

[2] N/A Not Applicable: the monthly line falls within the comfort zone and therefore there is no need for a cooling strategy

The plotting of monthly climatic lines for Beirut city (hot humid zone) shows that day time ventilation is expected to achieve comfort for the majority of the cooling season, except for about 11% of the time in August. Night time ventilations is only needed in August and indirect and direct evaporative cooling strategies ane not recommended for the majority of July and August, this is because of the high wet bulb temperature and humidity levels in these months that do not allow for evaporative cooling.

Amman:

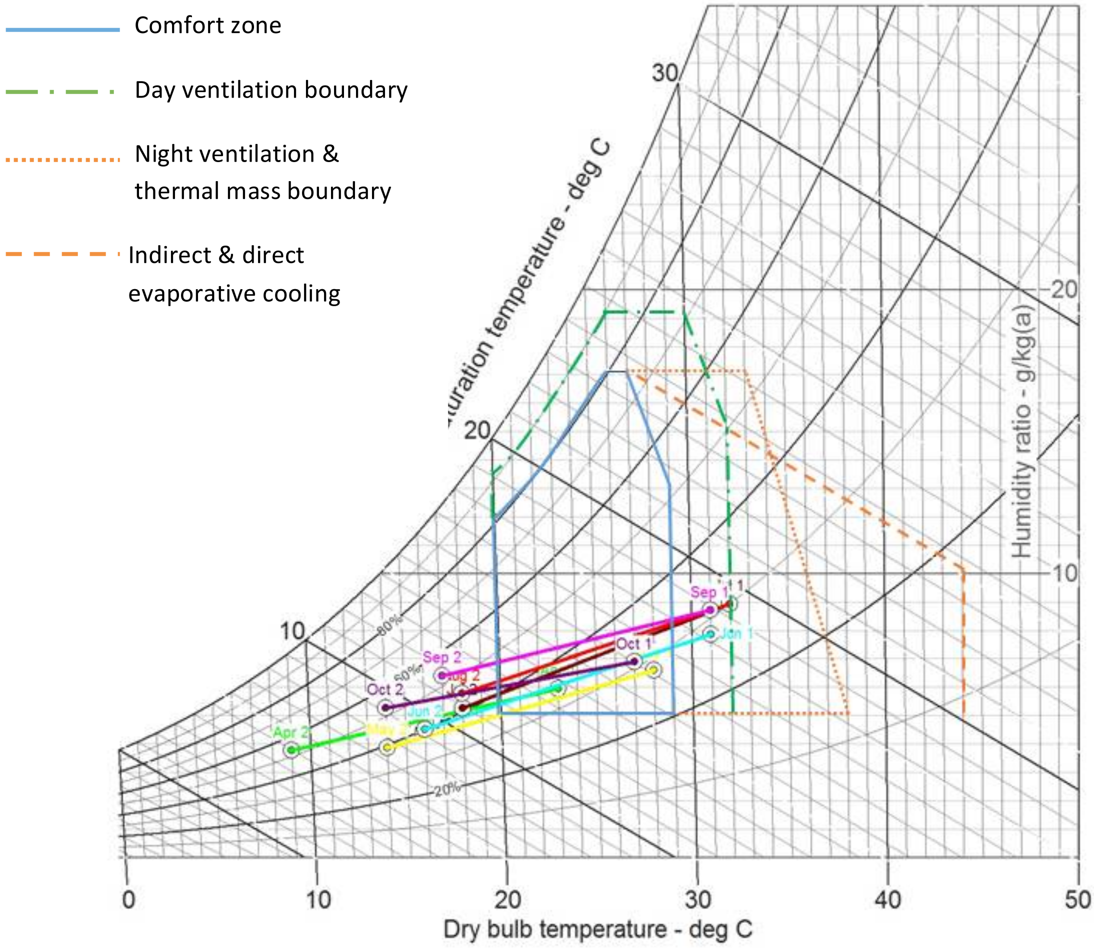


Figure 3.7: BBCC for Amman city as a representative of the warm dry zone

Table 3.5: Passive cooling strategies potential according to Figure 3.7; the table below shows for what percentage of the time comfort *cannot* be achieved (overheating), warm dry zone.

STRATEGY	APRIL	MAY	JUN	JUL	AUG	SEP	OCT
Day vent	N/A	N/A	0%	0%	0%	0%	N/A
Night vent	N/A	N/A	0%	0%	0%	0%	N/A
Evaporative cooling	N/A	N/A	0%	0%	0%	0%	N/A

Damascus:

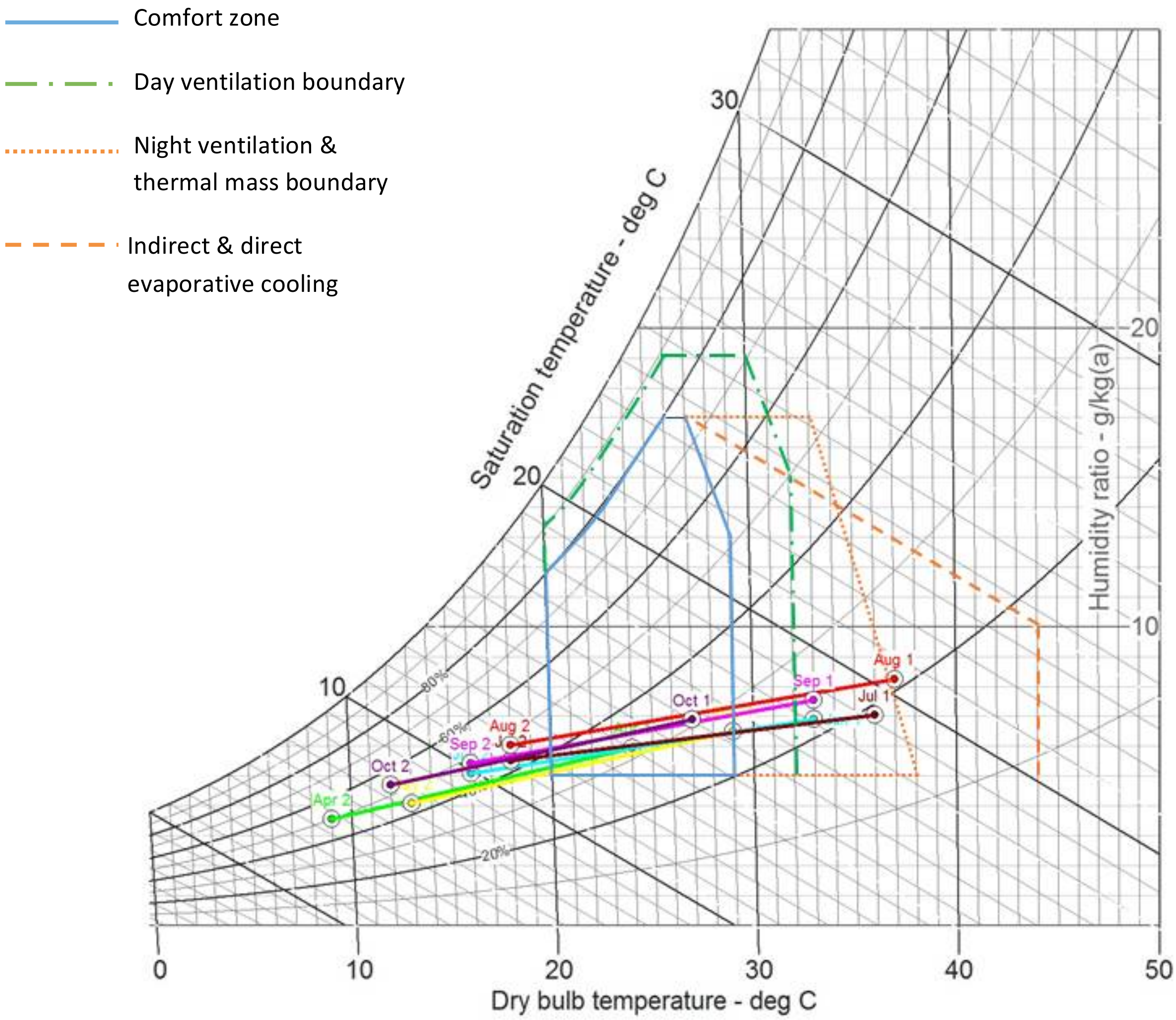


Figure 3.8: BBCC for Damascus city as a representative of the hot dry zone

Table 3.6: Passive cooling strategies potential according to Figure 3.8; the table below shows for what percentage of the time comfort *cannot* be achieved (overheating), hot dry zone

STRATEGY	APRIL	MAY	JUN	JUL	AUG	SEP	OCT
Day vent	N/A	N/A	5%	22%	26%	5%	N/A
Night vent	N/A	N/A	0%	0%	2%	0%	N/A
Evaporative cooling	N/A	N/A	0%	0%	0%	0%	N/A

In Damascus (the hot dry region), the Chart indicates that in April, May and October no cooling strategies are required, on the contrary temperatures fall below the lower boundary of the comfort zone indicating that some sort of heating might be needed. Natural day time ventilation is adequate to achieve comfort for the majority of June and September. Night time temperatures throughout the cooling season tend to fall below the suggested comfort zone, this is because of the large diurnal swing in this region that should allow for the exploitation of night time ventilation and is shown to be required in July and August. Evaporative cooling might be required for a limited time in August.

Aqaba:

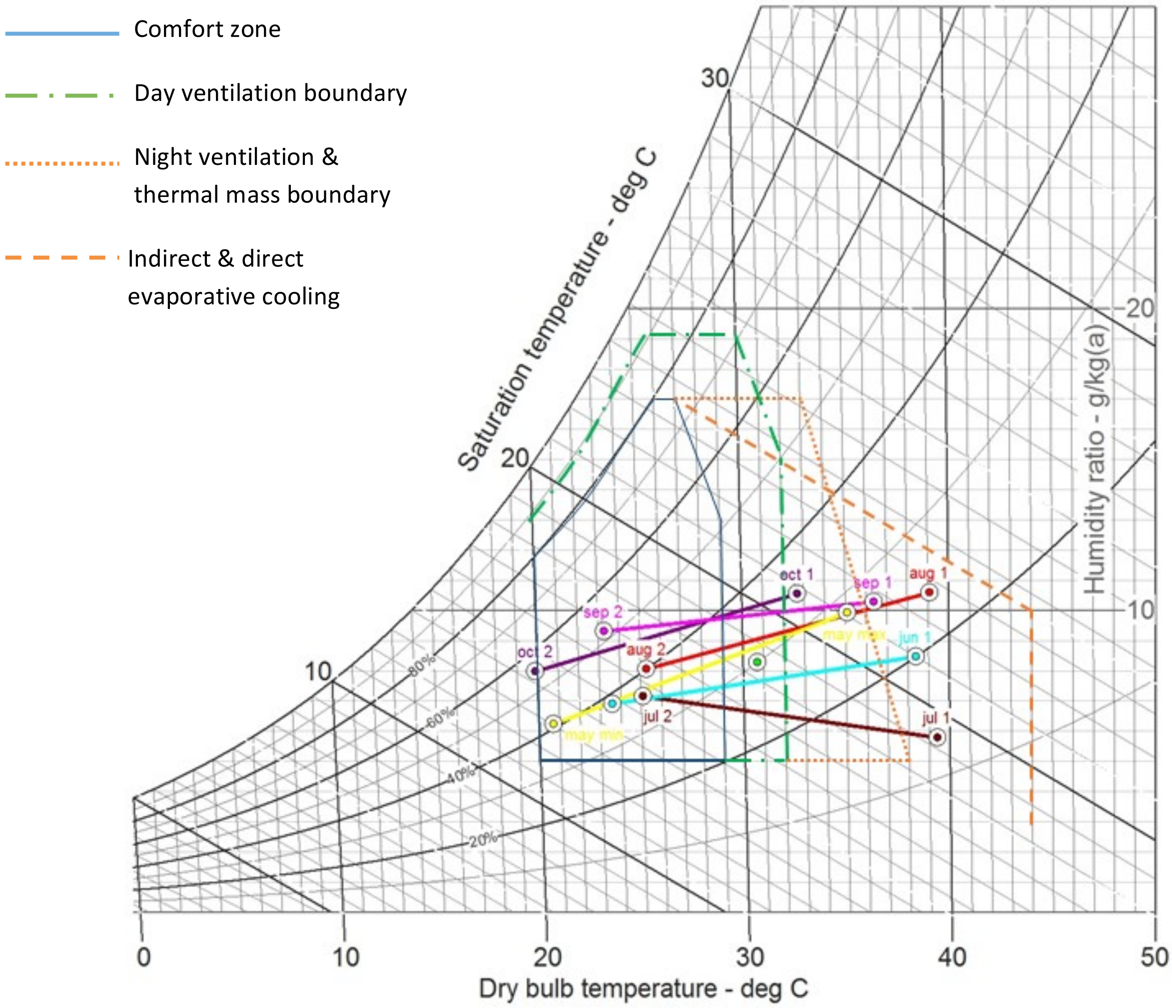


Figure 3.9: BBCC for Aqaba city as a representative of the very hot dry zone.

Table 3.7: Passive cooling strategies potential according to Figure 3.9; the table below shows for what percentage of the time comfort *cannot* be achieved (overheating), very hot dry zone.

STRATEGY	APRIL	MAY	JUN	JUL	AUG	SEP	OCT
Day vent	0%	21%	45%	52%	51%	33%	4%
Night vent	0%	0%	12%	14%	21%	4%	0%
Evaporative cooling	0%	0%	0%	0%	0%	0%	0%

In the very hot and dry region, day time ventilation isn't adequate to maintain comfort for the majority of the cooling season. Night time ventilation can bring internal temperature to comfort levels for the majority of Jun and July but additional evaporative cooling will needed in the hot months.

3.2.2 Hourly ambient weather conditions

Hourly ambient DBT and the corresponding moisture content, obtained from available weather files, for each month were plotted on the BBCC for each of Beirut, Damascus and Aqaba climates. Then the number of hours that fell outside the boundaries of a strategy were calculated, excluding hours that fell below the lower comfort limit 20°C as this indicated a heating requirement rather cooling requirement. In other words overheating hours were calculated. This showed a considerable discrepancy between this method's predictions and the plotting of monthly climatic lines in the hot humid zone (Beirut). While in the hot dry and the very hot dry zones (Damascus and Aqaba), the discrepancy wasn't as significant as it only resulted in approximately 10% or less, additional overheating hours. The following figures and tables illustrate this:

Beirut

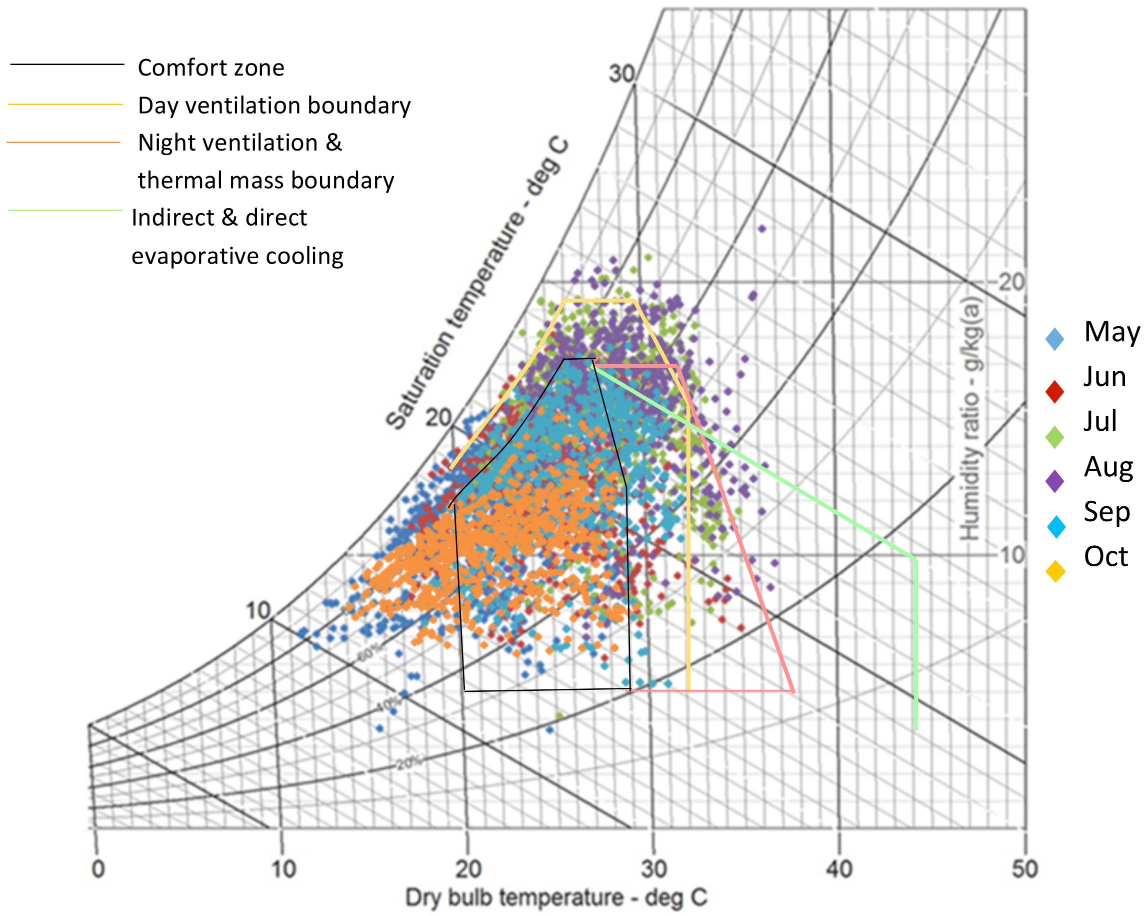


Figure 3.10: Hourly ambient weather on BBCC for Beirut

Table 3.8: Passive cooling strategies potential according to Figure 3.10; the table below shows for what percentage of the time comfort *cannot* be achieved (overheating)

STRATEGY	APRIL	MAY	JUN	JUL	AUG	SEP	OCT
Day vent	N/A	3%	8%	28%	26%	2%	0%
Night vent	N/A	4%	7%	22%	24%	1%	0%
Evaporative cooling	N/A	4%	8%	30%	37%	3%	0%

Damascus

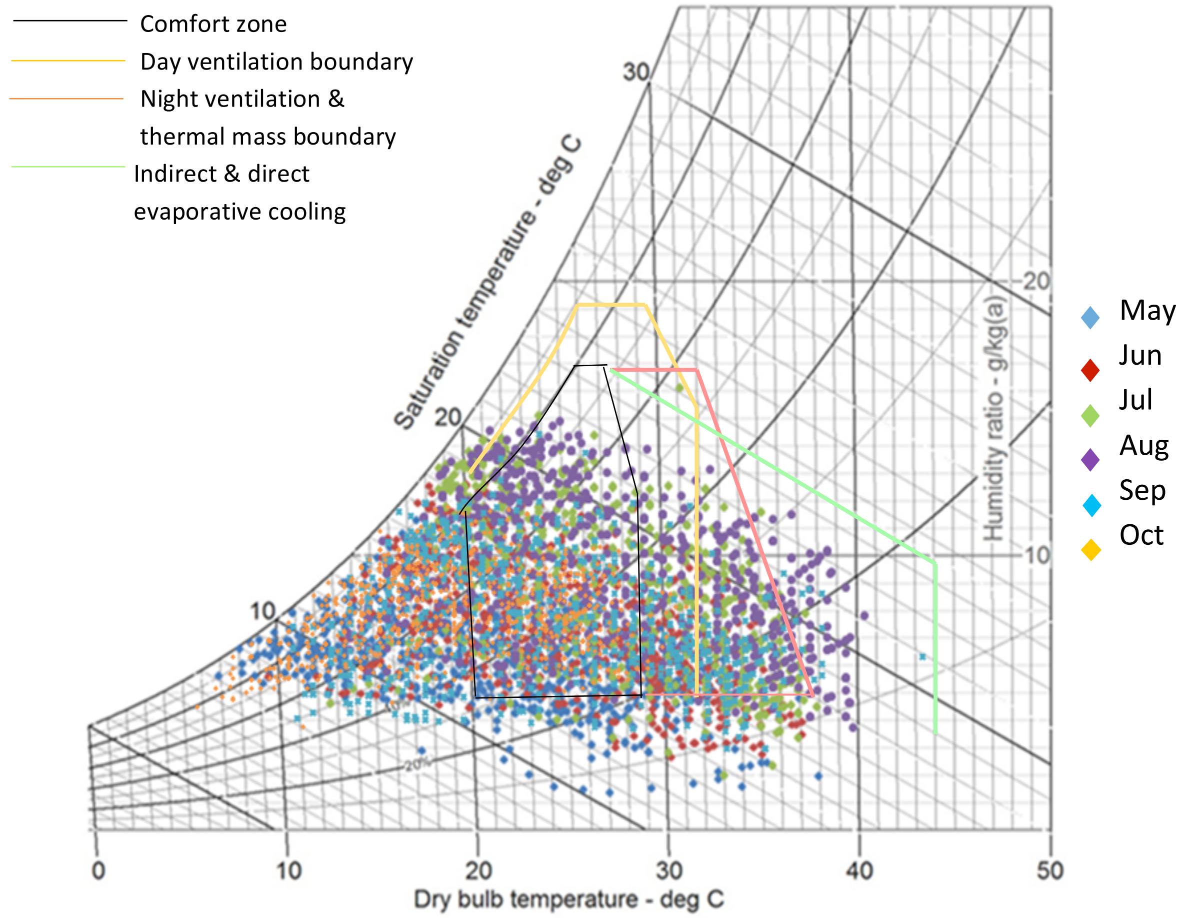


Figure 3.11: Hourly ambient weather on BBCC for Damascus

Table 3.9: Passive cooling strategies potential according to Figure 3.11; the table below shows for what percentage of the time comfort *cannot* be achieved (overheating)

STRATEGY	APRIL	MAY	JUN	JUL	AUG	SEP	OCT
Day vent	N/A	4%	13%	25%	28%	13%	N/A
Night vent	N/A	N/A	0%	1%	6%	0%	N/A
Evaporative cooling	N/A	N/A	0%	0%	0%	0%	N/A

Aqaba

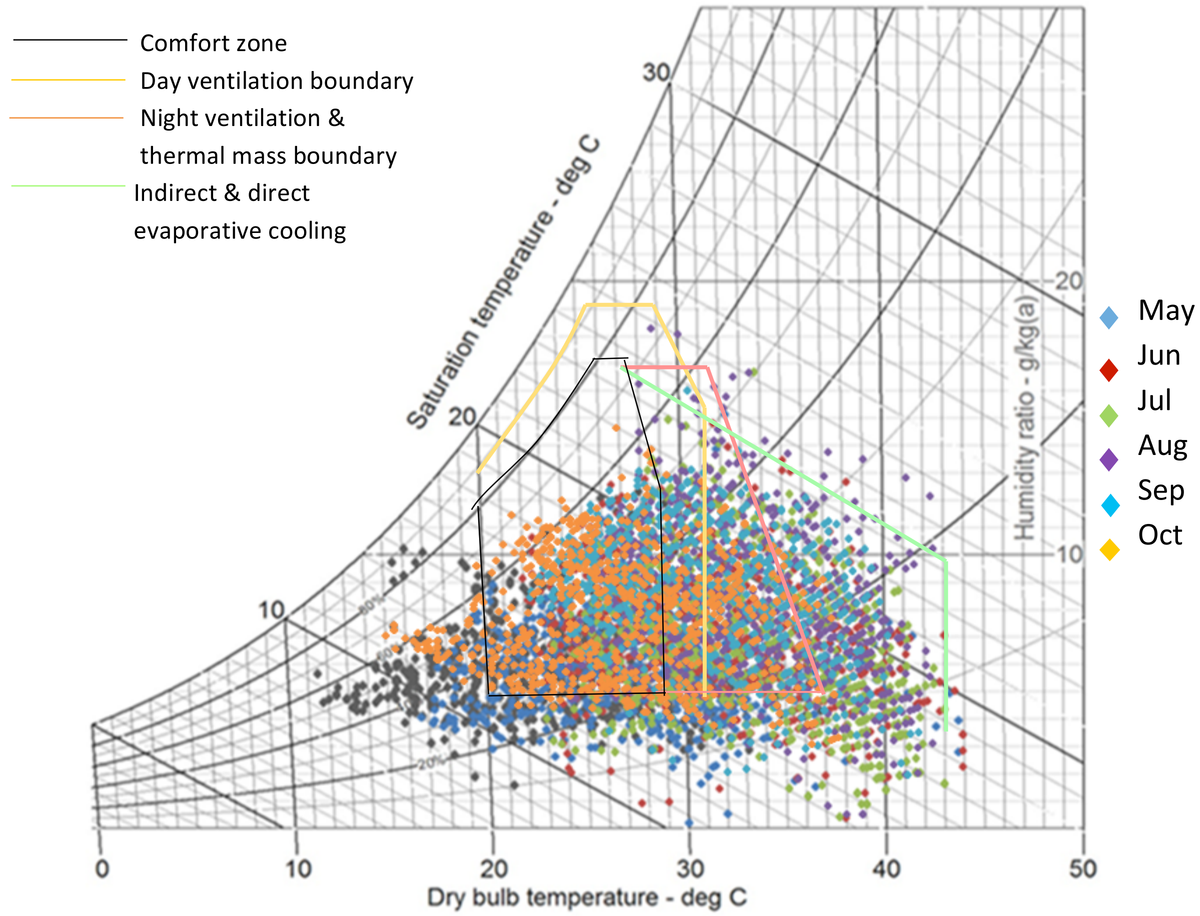


Figure 3.12: Hourly ambient weather on BBCC for Aqaba

Table 3.10: Passive cooling strategies potential according to Figure 3.12; the table below shows for what percentage of the time comfort *cannot* be achieved (overheating)

STRATEGY	APRIL	MAY	JUN	JUL	AUG	SEP	OCT
Day vent	6%	19%	47%	54%	55%	40%	15%
Night vent	0%	4%	15%	24%	25%	10%	0%
Evaporative cooling	0%	0%	0%	0%	2%	0%	0%

3.3 Thermal Comfort zones

In relation to the discussion in section [2.5] a comfort zone for the region being studied in this thesis needed to be defined. Firstly, representative cities in the main four climatic zones were selected based on availability of weather data (Table 3.3). Ideally adaptive thermal comfort surveys need to be conducted to establish the comfort zone boundaries in the region. However, due to the on-going conflict in Syria and its implications on neighbouring countries during the time of this research it was not possible to conduct a reliable comfort survey with adequate sample size. Therefore, the adaptive comfort equations suggested in ASHRAE standards 55-2013 were used to define an adaptive comfort zone for each of the four main climatic zones, because they are the only international standards available.

Firstly, comfort temperature upper and lower limits for 80% acceptability were calculated for each month using equation (1) and (2):

$T_{comf} = 0.31\ (T_{om}) + 21.3$ (1)

$T_{comf} = 0.31\ (T_{om}) + 14.3$ (2)

Where T_{om} is the monthly mean outdoor temperature calculated easily from meteorological record of outdoor mean maximum and minimum temperatures.

It should be noted here that ASHRAE standards allow using the 'monthly mean temperature' instead of the 'prevailing mean temperature' for simplicity and when no daily weather data is available. However, it recommends using the 'prevailing mean temperature' when used in conjunction with dynamic thermal simulation software. For the purpose of this research the use of monthly mean temperature is adequate as ASHRAE's preferred expression for T_{om}, the prevailing mean temperature, is an exponentially weighted running mean of a sequence of mean daily outdoor temperatures prior to the *day* in question. No one day is being examined here but rather a whole season.

Secondly, relative humidity as discussed in [2.3.3.3] is not accounted for in all existing adaptive comfort standards and equations. It is suggested that, when the upper comfort temperature limit exceeds 30°C and when the RH is higher than 70%, the upper comfort boundary is lowered by 1°C based on Nicol's findings, (Nicol, 2004). Upper relative humidity level is taken as 80% (Martinez et al., 2000) for the suggested comfort zones. Nonetheless, the climate in the EM is predominantly dry, the only zone that could be of a concern is the coastal zone. Summer comfort temperatures are summarised in table 3.11.

Table 3.11: Representative cities and thermal comfort temperature

	Zone	*Hot humid*	*Warm dry*	*Hot dry*	*Very hot dry*
	Temperature (°C)	Beirut	Amman	Damascus	Aqaba
Apr	T_{om}	18.0	16.0	15.8	23.9
	T_{comf} upper limit	26.9	26.3	26.2	28.7
	T_{comf} lower limit	19.9	19.3	19.2	21.7
May	T_{om}	22.0	21.0	20.1	27.9
	T_{comf} upper limit	28.1	27.8	27.5	29.9
	T_{comf} lower limit	21.1	20.8	20.5	22.9
Jun	T_{om}	24.5	23.5	24.2	31.0
	T_{comf} upper limit	28.9	28.6	28.8	30.9
	T_{comf} lower limit	21.9	21.6	21.8	23.9
Jul	T_{om}	27.0	25.0	26.7	32.3
	T_{comf} upper limit	29.7	29.1	29.6	31.3
	T_{comf} lower limit	22.7	22.1	22.6	24.3
Aug	T_{om}	27.5	25.0	26.4	32.2
	T_{comf} upper limit	29.8	29.1	29.5	31.3
	T_{comf} lower limit	22.8	22.1	22.5	24.3
Sep	T_{om}	26.5	24.0	23.2	29.9
	T_{comf} upper limit	29.5	28.7	28.5	30.6
	T_{comf} lower limit	22.5	21.7	21.5	23.6
Oct	T_{om}	24.0	20.5	18.5	26.3
	T_{comf} upper limit	28.7	27.7	27.0	29.5
	T_{comf} lower limit	21.7	20.7	20.0	22.5

3.4 Summary

In this chapter, the available climatic classification for the region was reviewed. Limitations in the Koppen classification for use in climate responsive design were identified and addressed. Bio-climatic zoning was established, resulting in six distinctive climatic zones, namely: a cool humid, a hot humid, a hot mild, a warm dry, a hot dry, and a very hot dry zone. Excluding the cool humid zone, the potential of passive cooling strategies suggested by Givoni for the major four remaining climatic zones was established using his BBCC. Two methods for using the BBCC, the monthly climatic lines and the hourly weather conditions, were evaluated and discrepancies between the two methods were reported. The potential of passive cooling strategies established by the BBCC will be compared to modelling predictions in Chapter 5. Additionally a comfort zone for each of the climatic zones in the EM was identified based on the discussion in Chapter 2.

Chapter 4: Defining Reference Buildings

In order to investigate the benefits of passive strategies in the selected hot climates and their limitations, reference buildings were selected for modelling using dynamic simulation tools and for short-term environmental monitoring. The focus of this research was on domestic buildings however due to the limited number of exemplars all building typologies that incorporated the passive cooling strategies outlined in the BBCC were reviewed in this chapter and then assessed in terms of availability of information for modelling, accessibility and suitability for monitoring.

4.1 Review of the current State of The Art

4.1.1 Vernacular architecture

It is well recognized that traditional buildings are well suited to their local climate; Heschong (1979) believed that vernacular buildings could be considered as a sophisticated way of thermal adaption. Vernacular buildings were naturally ventilated and their designs created a number of different microclimates, providing the opportunity for occupants to select the thermal zone that most suited them. In the hot and very hot arid regions the traditional Arabic courtyard house was the most prevalent typology. While in the warm humid region, another traditional houses called the central hall houses are found.

4.1.1.1 The courtyard house

The design of a traditional Arabic house represents a valuable solution to overcome the hot arid climate that dominates most of the region. The main characteristics of traditional Arabic architecture are;

- Compact urban planning to minimize solar gains and provide shading for outdoor pedestrians pathways,
- Closure to the outside and openness to the inside through a courtyard that functions as climate moderator,
- The provision of vegetation, a water source, and heavy thermal mass.

The best review available on the Arabic/Islamic vernacular architecture is found in Fathy, (1986) and Ragette, (2003). The courtyard house is traditionally found in the ancient cities of Aleppo and Damascus. These cities have a hot-arid climate where night-time air temperatures are 10° to 20°C lower than daytime temperatures. The courtyard house exploits this diurnal phenomenon by using night ventilation as a cooling strategy; windows are kept open at night so cool night air descends into the courtyard and then enters the rooms. The rooms preserve the coolness gained during the night till late in the day due to the building's significant thermal mass; however ventilation is still required late in the afternoon. Late afternoon ventilation applies the stack effect principle. This is exploited by designing the rooms that face the courtyards with two rows of windows; the air that was heated in the courtyard during day time gradually rises up creating motion and air circulation between the upper and lower windows, that is enough to ventilate the building interior spaces, (Fathy, 1986).

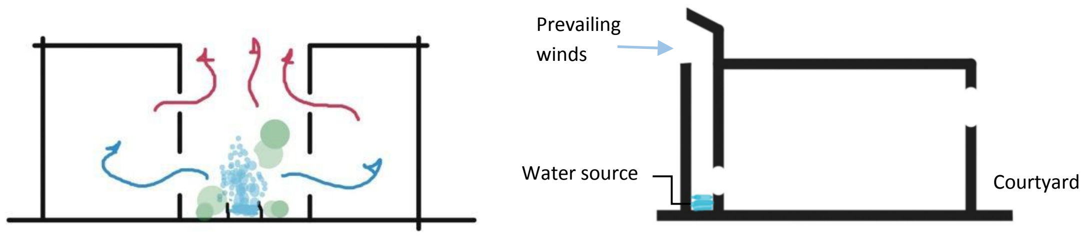


Figure 4.1: a sketch of the performance of courtyard (left), malkaf (right).

Additionally, different strategies were developed to mitigate the hot climate, such as the Mashrabiya, and the Malqaf. The Mashrabiyah refers to an opening with a wooden lattice screen where the lattice work defines small openings. The functions of the Mashrabiya are: to control light penetrating interior spaces, to control air flow, to reduce the temperature of the air and increase its humidity, and to ensure privacy, (Fathy, 1986). The wooden lattice, which is an organic fibre, absorbs moisture from the air at night and when hot air flows in the room during day the moisture in the wood is converted to vapour as it absorbs the heat from the air thus cooling it. The spaces between adjacent openings of the lattice are adjusted in relation to solar radiation and air flow required. The Malqaf is basically a vertical shaft that functions as a wind catcher. It has only two openings, a high-level inlet above the building facing the prevailing winds to catch the wind, and an outlet at the bottom of the shaft. The importance of this technique is that in hot climates, ventilation through windows is generally not adequate because wind velocity is decreased in urban settlements and thus the Malqaf increases air movement inside the room. In hot arid climates, the air coming through the Malqaf is cooled before entering the room by evaporative cooling by using a water source, such as wet mats or sheets, or a water container inside the Malqaf. Additionally it acts as a filter; any particles that are carried with the air will fall under their weight as the air enters the shaft. The size of the Malqaf is determined by ambient air temperature; as air temperature increases the size of the Malqaf decreases, (Fathy, 1986).

Another feature of the courtyard house is that the house is generally designed with different spaces to suit different seasons, allowing daily and seasonally vertical and horizontal movement between internal spaces, as a means of adaptation to the dominant climate. Vernacular examples such as, the Iwan, (the hall), walled on three sides while one side is completely open to the courtyard and facing north and used as a summer living area. Figure 4.1 & 4.2.

Figure 4.2: Almashrabiyeh (left), Iwan (right) (Alabidin, 2011).

4.1.1.2 The Central hall House

This typology mainly exists in the warm humid coastal region of the EM. This type of houses is known for its central hall that is open to all rooms of the house and its red-tiled pitched roof. Contrary to the courtyard house, the central-hall house has three large arched windows. The large windows are generally north facing, they provide abundant daylight to the interior and encourage wind-driven cross ventilation as in most cases they are open towards the sea. The central hall house design relies on cross ventilation and good shading for cooling (Hooper, 2011).

Figure 4.3: layout of the central hall house (Hooper, 2011)

4.1.2 Current non-domestic best practice

In the context of this subsection a building qualifies as best practice if it has been acknowledged for its energy conscious design in journals, or won high public acclaim internationally, through receiving an award for instance. It is acknowledged that these buildings may not perform as expected. However, they were considered to be the best available exemplars of energy conscious buildings in a region where very limited energy efficiency appraisal is available. The current non-domestic best practice surveyed was found to be limited to schools or education-related complexes. There are three exemplars in total that use passive and active strategies, table 4.1 summarises their similarities and differences, followed by a more detailed description for each of the buildings.

Table 4.1: best practice non-domestic buildings

		LYCEE CHARLES DE GAULLE	QOBBEH COMPLEX	CHARLES HOSTLER STUDENT CENTRE
LOCATION		Damascus Ha	Beirut Wh	Beirut Wh
PASSIVE STRATEGIES	Construction	Heavy weight	Heavy weight	Heavy weight + curtain walls
	Lighting	Natural daylight	Natural daylight	Natural daylight
	Shading devices	Light removable shading devices	Horizontal & vertical louvers	Overhangs and fins
	Layout	courtyards	courtyards	courtyards
	Ventilation	Cross ventilation + night cooling	Cross ventilation + night cooling	Mechanical ventilation
	Passive cooling elements	Solar chimneys	Fan-assisted wind tower	Roof gardens
ACTIVE STRATEGIES		none	fans	geothermal radiant cooling system

4.1.2.1 Lycée Charles de Gaulle, Damascus, 2008

The French school located in Damascus city was designed by the French architects Ateliers Lion together with the German environmental engineering firm, Transsolar. The building relied mostly on passive design strategies and the design combined technology with traditional architecture. The school is funded by the French ministry of foreign affairs; the objectives set by the French government were to minimize building operation costs (energy, maintenance), in addition to providing thermal comfort conditions in the classrooms. The main characteristic of the school as described by Elgendi, (2010) are:

Construction: High thermal mass using heavy weight concrete materials.

Layout: the building layout is open to the west and it consists of two clusters of small buildings that are connected via small courtyards.

Shading: the courtyards are covered with light removable shading devices that function differently according to the season; in summer they provide shade and solar protection during daytime and they are then opened at night to allow radiative cooling to the night sky. In winter they are opened during the day to capture solar gains and then closed at night to preserve the heat gained during the day.

Cooling strategy: Night cooling and cross ventilation, vegetation in the courtyards in addition to wind-assisted solar chimneys; cool air is driven into the classrooms via their windows from the moderated climate of the courtyard and through small earth ducts in the floor slab to pre-cool air temperature. Warm air is then driven out by the solar chimneys. Since earth temperature is steady all year round, the function of the ducts is reversed in winter. The solar chimneys are oriented towards the south and are covered with black-painted polycarbonate sheet to trap solar radiation at the top of the chimney in order to enhance the stack effect inside the chimneys, pulling warm air from the classrooms below. Occupant control was provided via operable louvers inside the classrooms at air intakes and outlets.

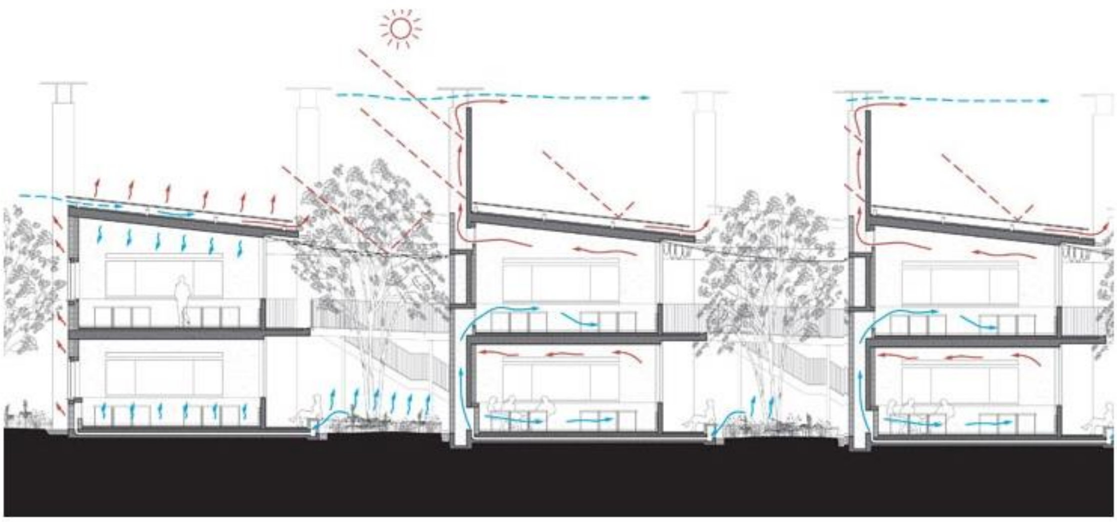


Figure 4.4: passive cooling strategy (Elgendi, 2010).

4.1.2.2 Qobbeh educational complex, 2012

This complex of buildings is located on the Mediterranean cost south of Beirut. The buildings consist of a dormitory, school, nursery, auditorium, a library and other services. The project was designed by Prime Design Architects in collaboration with Architect Maha Nasrallah as a prototype for a climate-responsive educational facility. The main objectives set by the client were to reduce operative energy costs for cooling and to enhance the environmental quality of the project. No active systems were used except for ceiling mounted fans in addition to solar heating system. Thus the complex design relied mainly on passive strategies to keep it within comfort levels. Additionally, attention was given to reduce costs and environmental impact of the project by using local materials and re-use of the stone materials extracted onsite from excavation work, (Primedesignpea, 2013; Yeretzian, 2013).

Construction: Thermal mass, twin-layer external air-cavity walls (4400mmthick) and insulated roof (3200mm thick). The double layer wall resulted in reducing the thermal gains by 45% when compared with single layer walls. The classrooms and the cafeteria also benefited from low e-coating glass. All building materials used were locally sourced and manufactured.

Layouts: courtyards, creating micro climates.

Shading: Horizontal and vertical louvers.

Cooling strategy: Natural cross ventilation in the classrooms and the dormitory bedrooms that are oriented to benefit from the prevailing south-west winds. In addition to fan assisted wind towers in the cafeteria where cross ventilation cannot be applied due to its great depth.

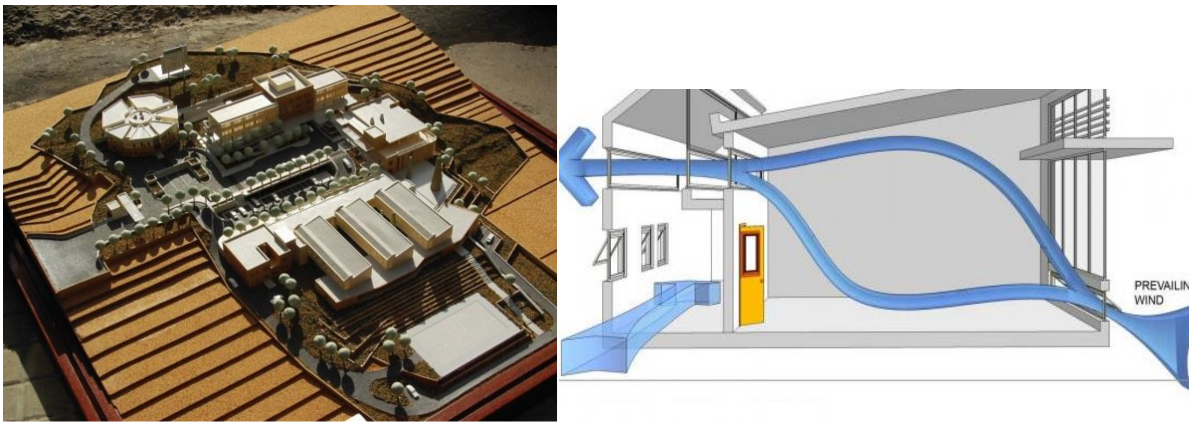


Figure 4.5: site plan and classroom ventilation strategy. (Yeretezian, 2013).

4.1.2.3 Charles Hostler student centre, Beirut, 2008

The Charles Hostler student centre is located within the American University of Beirut (AUB) campus in Beirut, Lebanon, at the edge of the Mediterranean Sea. The Hostler Centre is named one of the American's Institute of Architects (AIA) Top Ten Green Projects for 2009. The Hostler Centre was designed to be self-sufficient using passive design strategies and active systems; the main driver behind this choice was a response to the repetitive electricity blackouts in peak hot summer months due to the damage that the Beirut infrastructure suffers from after the several wars that have taken place in the last two decades. Therefore, sustainability and minimizing reliance on energy to provide cooling and lighting to the interior spaces were main design objectives, and thus the design was a result of integrated studies of air movement, solar access, and shading. The centre incorporates the following strategies (Yoos & James, 2007; Elgendy 2011), Figure 4.6.

Construction: local and durable building materials were used for construction and cladding, such as Syrian sand stone for cladding and concrete construction. The building is highly insulated, cavity walls with U-value of 0.7 W/m2K are incorporated and low-e glazing is used. Roof gardens

Layout: the building Layout is divided into multiple building volumes as a result of shading and ventilation studies. The volumes are connected by pathways and gardens, and oriented to face west and east, creating courtyards that are self-shaded as the different building volumes cast shadows on each other. Moreover, the massing of the building into multiple clusters allowed natural cooling to the spaces from sea breezes.

Shading: to mitigate the heat gain implications of this orientation on the east and west facades, the two facades were designed mostly as solid masonry walls, with highly glazed curtain wall facades applied to walls to the north and south faces. Integral shading devices are used to shade interior spaces from direct sunlight, such as pre-cast concrete louvers and aluminium fins. These shading devices were placed with consideration of different orientations.

Cooling strategy: The Centre incorporates active systems that are used for cooling, heating and ventilation. For cooling, a highly-efficient sea-water geothermal radiant cooling system is used to radiantly cool the gymnasium, the swimming pool, the theatre, squash courts, and the café.

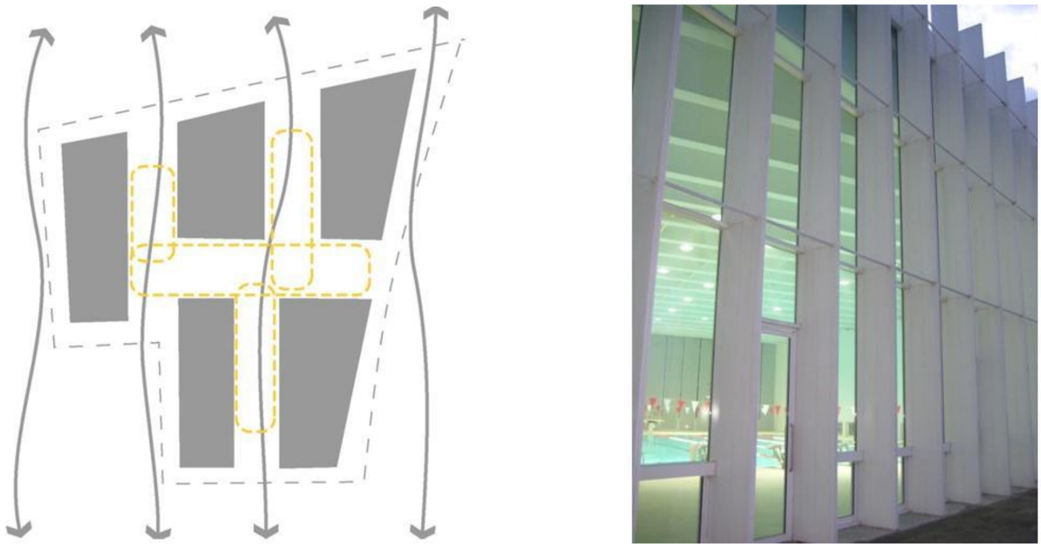


Figure 4.6: Ventilation (Elgendi, 2010) and shading strategies.

4.1.3 Domestic best practice

Although the vast majority of domestic buildings in the EM region are apartment blocks, the only best practice exemplars are privately owned houses. Table 4.2 summarizes their main characteristics.

Table 4.2: Best practice domestic buildings

		AQABA HOUSE	CASA BATROUN
LOCATION		Aqaba V-Ha	Batroun Wh
PASSIVE STRATEGIES	Construction	Heavy weight	medium weight
	Lighting	Natural daylight	Natural daylight
	Shading devices	Venetian shutters, window recess & horizontal louvers	Venetian shutters, window recess & overhangs
	Layout	Terraces	Terraces
	Ventilation	Cross ventilation + night cooling	Cross ventilation + night cooling
	Passive cooling elements	Green roofs + fountains	Green roofs
ACTIVE STRATEGIES		A solar-driven adsorption cooling system	Fans

4.1.3.1 Al Aqaba house: the first low energy house in Jordan

This house won The Energy Globe Award in 2007. The Aqaba residential building, located in Al Aqaba city south of Jordan, was built as a prototype to promote low-cost environmental design in the region. The demand for housing in Al Aqaba city was expected to triple by 2025. Therefore, the house owner who is a Jordanian environmental researcher lunched a competition for low-cost energy efficient house that stayed close to conventional building practice in the region. The winner was a Dutch Architect Florentine Visser. The project was co-funded by European bodies such as the MED-ENEC European Union and GTZ. The house is composed of three stories with a total area is 420 m^2.

Construction: heavy weight construction, walls thicknesses varied from 440 mm to 470 mm, and roof thickness between 514 mm to 719 mm (in the case of the roof garden). The wall construction comprises a sand-filled cavity walls, stone cladding, plaster with a straw finish, plus Insulation.

Layout: The building is oriented with bedrooms towards the north and east to protect the interior rooms from summer afternoon heat. The zones towards the west side are buffer areas with a short term use; as corridors and bathrooms.

Shading: Venetian shutters to allow shading and ventilation and encourage night ventilation, recessed windows in the thick walls.

Cooling strategy: Cross ventilation through careful placement of windows and doors. The staircase tower works as an outlet wind tower; a ventilation opening in the staircase to help draw cooler air from the house windows. In addition, small openings below the ceiling as heat outlets to improve night-cooling.

Outdoor evaporative cooling: vegetation, and for evaporative cooling of incoming air a water fountain is installed outside the kitchen window.

An underground cooling system is incorporated in the floor of the living area (subsoil cooling). The outdoor air flow through PVC pipes that are embedded in the soil, thus the heat is released into the soil reducing the air temperature of the incoming air.

Other features:

A solar-driven adsorption cooling system is installed on the top roof. The solar hot water matrix delivers domestic hot-water, heating and energy for the adsorption chiller, which delivers cooling at a high efficiency rate.

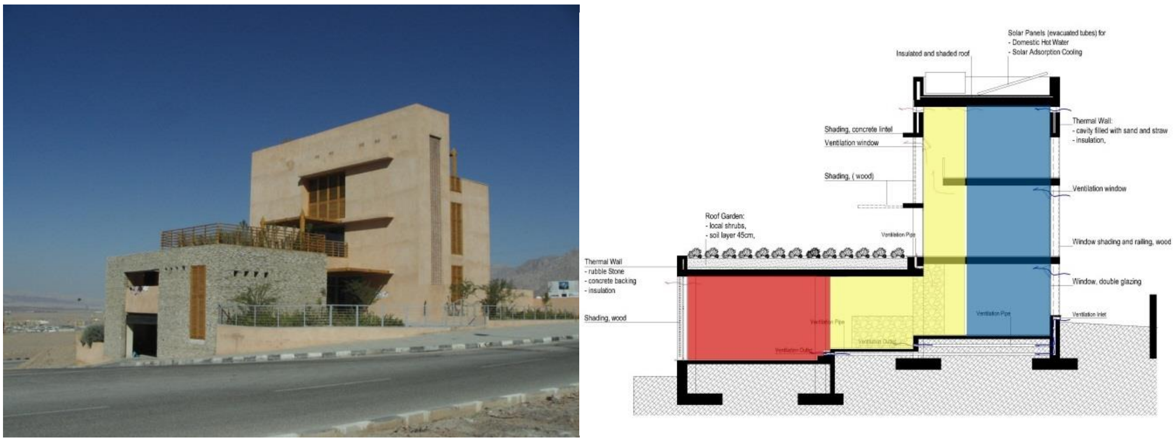


Figure 4.7: high thermal mass, and zoning strategy (red: warm, yellow: buffer zone, blue: cool), (Visser, 2007).

4.1.3.2 Casa Batroun, Batroun 2013

The house is located in Batroun city in Lebanon on the Mediterranean Sea, 50km north of Beirut. It is the first and only awarded BREEAM excellent house in the region. The house was originally a vernacular building about 150 years old that was refurbished by Architect Maha Nasrallah and Consultant Maya Karkour in 2012-13. The original house design was similar to the central-hall house design and allowed cross-ventilation. The refurbishment included insulating the house and also changing its layout, the roof was removed and a new floor was added using timber construction. The ground floor and the first floor are separated for two different dwellings. Figure 4.

Figure 4.8: Casa Batroun

Construction: the ground floor is consisted of the old masonry shell while the 1st and mezzanine floors are newly built timber construction, all the walls and the roofs are internally insulated, the roof of the mezzanine level is a roof garden.

Layout: the building has a compact design but allows cross ventilation from all directions.

Shading: Venetian shutters to allow shading and ventilation and encourage night ventilation, recessed windows in the thick walls.

Cooling Strategy: Cross ventilation through careful placement of windows and doors.

Other features: Rain water harvesting**,** solar water heating and low energy appliances & LED lighting

4.2 Suitability for modelling and monitoring

Most of the vernacular heritage of the arid region is in Syria's two largest cities of Aleppo and Damascus. Given the current 'war-zone' status in Syria at the time of writing this thesis, it was not possible to assess the thermal comfort conditions offered by its vernacular buildings. Also, few courtyard houses were available in Lebanon and Jordan, however, they did not incorporate strategies such as Almalqaf and Almashrabiyeh mentioned in section [4.1.1.1]. Similarly most of Lebanon's central-hall houses were destroyed in the several wars that took place there.

During a visit to Jordan (Dec 2012), and Lebanon (Aug 2013) an attempt was made to find suitable vernacular buildings for modelling and monitoring. After a field survey and interviews with several architects and researchers in Jordan, (Zaiter, Aletan, Abu Ghanimeh, 2012) and Lebanon (Karkour, Yertzian, Arbid, Nasrallah 2013), it was concluded that the very few vernacular houses available in Jordan and Lebanon were not suitable as case studies. This was either because no detailed information of the construction and plans were available, no access was possible for monitoring, or other issues such as, modification of the original function, glazing the courtyard, conversion to air conditioned spaces and others that meant that the passive cooling strategies originally implemented were no longer in use.

As for new-built best practice, information was available and access was granted for dwellings in Al Aqaba in southern Jordan, Casa Batroun and the Al Qobbeh complex in Lebanon. Figure 4.9 summarises the climates and strategies considered by studying these buildings.

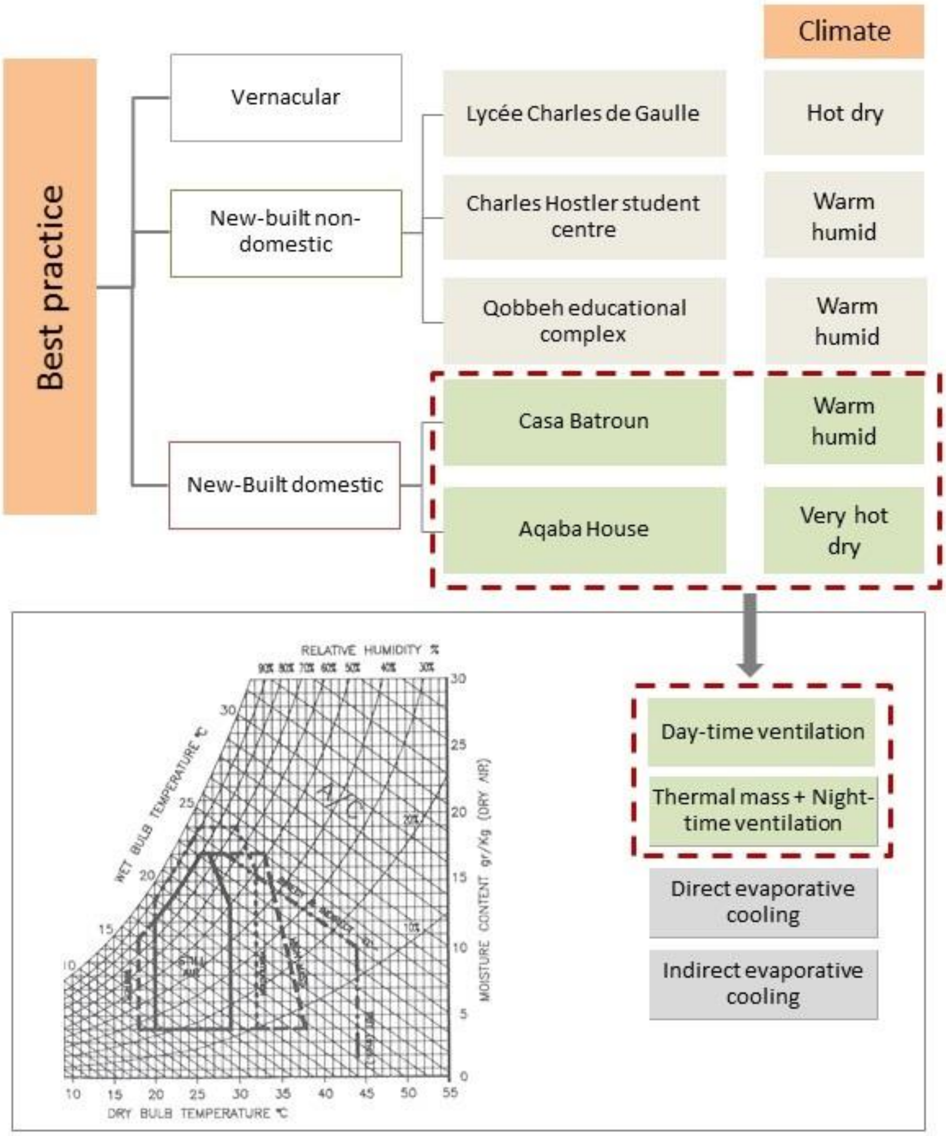


Figure 4.9: the selected reference buildings, climate and the passive strategies studied.

The two selected buildings had several design strategies in common, mainly they both installed Venetian shutters on most windows for shading and privacy, had roof gardens and an internal layout that allowed cross ventilation. The main difference was in construction types, where the house at Aqaba had thick insulated walls of concrete blocks, and the house at Casa Batroun had a combination of timber and masonry. Another difference was that the internal volumes of the three floors of the house at Aqaba were connected via the staircase well, while in Casa Batroun the ground floor was completely separate from the mezzanine and the first floor. Further description of both buildings and their constructions follows in Chapter 5 where these reference buildings underwent detailed dynamic simulation.

Chapter 5: Modelling of Selected Reference Buildings

In this chapter the use of computer modelling was employed to simulate the indoor environmental performance of a group of buildings considered to be 'best practice' in the EM region. Specifically, the influence of building form and design and the interaction of thermal mass and shading was evaluated in relation to the position of the climatic boundaries on the BBCC suggested by Givoni. To achieve this, computer building energy simulation tools and weather files were appraised and selected, and preliminary modelling was done to identify the key modelling challenges. Then the selected best practice domestic buildings in chapter 4 were modelled and the results compared with the BBCC predictions. The sensitivity of the modelling output in relation to input assumptions were evaluated, and finally a parametric analysis was carried out to establish the impact of ventilation rates, thermal mass and solar gains on the performance of naturally ventilated buildings.

5.1 Review of available dynamic building simulation tools

Building simulation tools are used to model buildings' energy consumptions or buildings' passive performance and strategies such as natural ventilation. Two modelling approaches are the most suitable for predicting ventilation potential in partitioned buildings: The first is Computational Fluid Dynamics (CFD) models that provide detailed and accurate air pressure, air velocity and temperature distribution within a single zone and between zones in addition to concentrations of water vapour, contaminants and turbulence parameters (Chen, 2009). The second approach is multi zone airflow networks. They assume a well-mixed condition within each room/zone and simulate the airflow between zones (Chu et al., 2010). Airflow networks are integrated in Dynamic building energy simulation tools using several coupling methods with the thermal model. Zhai et al (2011) reviewed studies that compared these coupling techniques, namely the "onion" method in which both the thermal and the airflow models are solved simultaneously at each time step, and the "ping-pong" method where the output of one model are fed into the other in the next time step and then back into the first model and so on in an iterative procedure. Both methods, the onion and the ping-pong, have their pros and cons depending on the complexity of the building and the length of the time steps selected.

An assessment of various types of models for predicting ventilation (including multi-zone airflow network models and CFD models) by Chen et al (2010) concluded that no universal model is available. CFD models offered the most accurate and detailed information about the performance of a naturally ventilated zone; however for annual whole building analysis multi-zone network models were recommended. The complexity and the long computing time in CFD models are why CFD analysis is generally used to predict airflow and temperature patterns at selected points in time and not a full-year analysis of an entire building (Johnson et al., 2012) as in (Lomas et al., 2007; Chiang et al 2012; Rajagopalan & Luther 2013; Bassiouny & Koura 2008). As the purpose of this research is to assess the long-term (the summer season) internal thermal conditions achieved by natural ventilation, it was best to use dynamic simulation modelling tools (DSM) that use airflow networks to assess their cooling potential.

There are several programs and detailed energy simulation tools available to predict the energy and thermal performance of buildings. A comprehensive list of building energy software tools is provided by US Department of Energy, (DOE, 2014), that account for 417 energy tools, of which 142 are a whole building energy simulation tools. These tools are currently in use worldwide in 32 countries, of which six are developing hot countries, namely; Brazil, Chile, Egypt, India, Pakistan and South Africa, while no tools listed to be in use in the region under consideration in this research. DSM are used to predict energy consumption in heated or cooled buildings (Blight & Coley, 2013), natural ventilation potential in free-running buildings (Lomas and Ji, 2009), and hybrid and mechanical ventilation performance (Yassine et al., 2012). Although most DSMs were validated against measured data, it is not uncommon for different DSM tools to offer different outputs. Schwartz and Raslan (2013) compared the three most commonly used tools EnergyPlus, Tas and IES-VE, by summarising their main characteristics and then used all three to model the same building with identical envelope parameters, systems and weather files. They found considerable variations in the energy output predictions, Figure 5.1. They attributed these variations to; algorithms differences, differences in the required input data and difficult to eliminate human error.

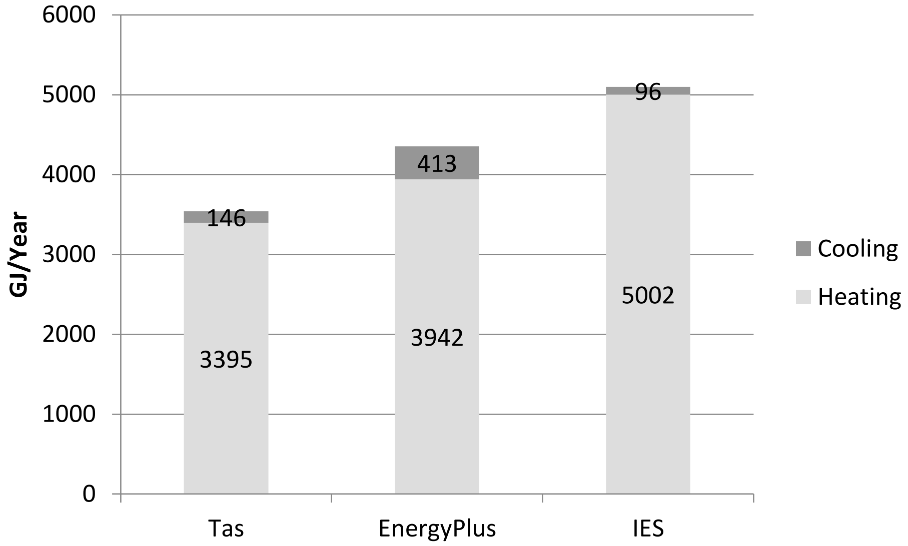


Figure 5.1: adapted from Schwartz and Raslan, (2013), energy simulation using epw Weather file.

For energy consumption several comparative studies between tools' energy use predictions and against measured data are available in the literature and a performance gap between predicted and actual energy use in buildings is frequently reported (Zero Carbon Hub, 2013; Schakib-Ekbatan et al., 2014; Branco et al., 2004). This gap varies in magnitude from case to case depending on several factors. DSM require detailed input data that are not always available, resulting in a number of uncertainties, simplification and poor assumptions for hard to measure variables that will impact the output and the predicted performance. Thus, the performance gap has been attributed to several causes that are either related to the shortcomings of the modelling tool used, namely; the reliability of the built-in equations and algorithms in the modelling software and the availability of reliable weather files (Zhai et al., 2011). Or related to poor simulation assumptions, namely; occupants' behaviour, patterns and occupant-controlled variables (Bordass et al., 2004; Menezes et al., 2012; Daly et al., 2014), issues with the built quality (Menezes et al., 2012; Nieman, 2007 and Gommans, 2008 cited in Guerra et al 2013) and poor assumptions regarding air-tightness and infiltration rates (Egan, 2011).

Fewer studies exist that compare the real and predicted performances of naturally ventilated buildings so less is known about potential factors that might contribute to the deviation of predicted performance from the real performance. A validation study by Haghighat and Li (2004) was conducted to compare three multi-zone air flow models against measured data from a four-room dwelling in a climatic chamber. The study found that the results predicted by the three models were identical however they were significantly different from the measured data. Zhai et al., (2011) argued that the underlying theory in all multi-zone air flow networks is essentially the same, which is why they tend to predict similar results. They chose EnergyPlus to evaluate the performance of three real non-domestic buildings against measured data and the study suggested that the models possibly over-predict the buoyancy driven flows in multi-story buildings. Additionally, it highlighted the importance of accurately measuring volume flow rate data, effective orifice area and discharge coefficients for vents used in real buildings. It also revealed that additional relationships to describe horizontal openings are needed. However, regarding horizontal openings, EnergyPlus documentation clearly states that measuring air circulation within a thermal zone through such openings is one of the deficiencies of airflow networks (EnergyPlus input output reference, 2013; Gu, 2007).

When surveying recent literature from 2005 onwards, on computer modelling of naturally ventilated buildings, it was found that EnergyPlus, Esp-r and IES VE are the most commonly used tools. Crawley et al., (2008) conducted a comparative survey between twenty main DSM. The comparison was based on information provided by the programs' developers and it included information on the capabilities of the models and validations. For ventilation analysis, nine capabilities were compared, namely:

1- single zone infiltration,
2- automatic calculation of wind pressure coefficients,
3- natural ventilation,
4- multi-zone airflow,
5- hybrid natural and mechanical ventilation,
6- control window opening,
7- displacement ventilation,
8- mix of flow networks/CFD,
9- contaminants

IES VE software was shown to have most of the capabilities required (the first seven), although more recent versions of IES include CFD modelling as well, ESP-r has fully or partly implemented eight of the capabilities, EnergyPlus and Tas have six. Although most of those DSM tools have undergone major and rapid developments, Crawley's study remain the most comprehensive to date.

In this study computer software Virtual Environment IES 2013 was used to undertake the simulation. It is approved energy software in the United Kingdom for energy analysis and Part L regulations (DCLG, 2014). It is the most common choice for UK designers because it offers 'level 5 accreditation' required for part L compliance via DSM. Additionally it is extensively used internationally and in several studies of naturally ventilated buildings (Lomas and Ji, 2009; Ji et al, 2009; Ahmed & Wongpanyathaworn, 2012; Rajagopalan & Luther, 2013). The program comprises an integrated suite of applications, only four of that were used in this modelling work; ModelIT for the basic building geometry, SunCast for shading analysis, ApacheSim for thermal simulation, and Macroflo that is the natural ventilation bulk airflow model.

5.2 Review of available weather data sets

Weather files consist of weather data for 12 months of the year in hourly time steps. They aim to represent the typical weather in a given location over many years in a single year data that could be used in simulation software. There are several available hourly weather files for use in dynamic building energy simulation. These files can be classified in three main categories. A single contiguous year selected from a period of record of historical weather data, a composite year compiled of 12 separate months from a period of record, and a synthetic year composed of synthetically generated hourly weather data (Kershaw et al., 2010; Crawley 1998).

The first type of weather files (United States Test Reference Year US TRY) was developed by the US National Climatic Data Centre in 1976, one of the main issues with such 'US TRY' files was that it lacked solar radiation data, also the US TRY year was selected from actual historic weather years in a period of record, excluding years that had months of extreme conditions, resulting in the selected year being a mild one. In 1981 Typical Meteorological year TMY was developed and it included solar radiation data that were either recorded or calculated based on cloud cover and type. Additionally it was a composite year where individual months that were the closest to the weighted long-term distribution were selected from actual weather period of record rather than entire year. WYEC format was developed by ASHRAE in 1985, both TMY and WYEC formats were updated in subsequent years. IWEC weather files by ASHRAE included nine weather variables but with different weighting factors dependant on their relative importance. Other common types of weather files include CIBSE TRY files that are similar to the TMY mentioned above.

Weather file formats have a significant impact on the reliability of the predicted energy use or environmental performance of modelled buildings with several studies showing that using different formats resulted in different simulation outputs. For example, Crawley (1998) examined the variation in simulated energy results using (DOE-2.1E) when using local measured weather data for 30 years and several weather data sets for an office building in 8 different locations in the USA. The author recommended that single year data such as TRY should not be used in DSMs as they were not representative of typical long-term weather. Composite synthetic years were more representative, such as TMY2 and WYEC2. He also found that the simulation results of TMY2 weather data sets best matched the simulation results of the local measured weather data (Figure 5.2). These findings are consistent with the findings of a study by Michopoulos et al. (2012) that evaluated different weather files formats namely, IWEC and TMY2 for the Thessaloniki-Greece area. This study also found that TMY2 weather file results were the closest to the measured annual energy consumption.

There is a lack of weather files for the locations studied in this research and the only weather files available for the EM region are the IWEC file for Damascus, Syria, MSI files for several cities in Israel, and an IWEC file for Larnaca in Cyprus. The selected best practice buildings were located in Beirut and Aqaba. No weather files were available for Aqaba city in Jordan, instead the weather file for Eliat city in Israel, (only 4km away from Aqaba) was used. The weather file is an MSI file, developed by the Faculty of Civil and Environmental Engineering, Technion - Israel Institute of Technology, Haifa, Israel, from data provided by the Israel Meteorological Service (IMS). It was provided by US DoE in EnergyPlus 'epw' textbased format derived from the Typical Meteorological Year 2 (TMY2) weather format. Weather variables included were dry bulb temperature, wet bulb temperature, dew point, relative humidity, atmospheric pressure, horizontal infrared radiation, global, diffused and direct solar radiation, wind direction and speed. However, the total cloud cover was simply stated as 5 decas all year round.

Similarly no weather file for Batroun city in Lebanon was available; the nearest location with a ready-to-use weather file was Damascus. However, Damascus weather is very different from that of the coastal EM region as demonstrated in Chapter 3. Therefore, options available were to, either use a weather file for a nearby city along the EM costal line such as Larnaca, or obtain a weather file from a private source. A list of private sources was available on the US DoE website. Meteonorm software used by many researchers to produce weather files for any location (Meteonorm, 2015) was considered among other providers. Meteonorm uses a statistical approach to produce hourly data from monthly values and for Beirut city Meteonorm uses temperature and wind monthly values from meteorological ground station and global radiation from satellites data (Muller, 2014). Such a statistical approach does not demonstrate the normal hour-to-hour and day-to-day variability seen in measured data. Weather Analytics, a private sector company that provided weather files in EnergyPlus 'epw' format was also considered. For Beirut, the files were compiled by integrating hourly weather station observations OLBA and the new NOAA reanalysis data sets. Solar radiation data for Beirut were not available from Lebanon Meteorological station OLBA, therefore the solar radiation used in the Weather Analytics weather file for Beirut city is from the Climate Forecast System Renalysis CFSR data set (Anderson, 2014). A TMY3 weather file for Beirut city was purchased from Weather Analytics, however it was found that the daily DBT was generally average and didn't represent the daily variation observed in reality. Therefore, it was best to use Larnaca IWEC weather file.

5.3 Preliminary testing

Prior to modelling the best practice domestic buildings selected in Chapter 4, preliminary modelling of a naturally cross ventilated room was conducted to establish a general understanding of the main factors that influenced the internal temperature of a naturally ventilated room with no heating or cooling system in use during the summer season (Figure: 5.2 and Tables 5.1 & 5.2). The Damascus IWEC weather file was used and different window opening schedules were evaluated. The results of this preliminary modelling were not conclusive. This is because it was undertaken mainly to help form a broad picture of the modelling challenges that were to be expected; and to assess the impact of changing certain design parameters such as thermal mass, ventilation rate, glazing ratios and ventilation time of the day on the natural ventilation performance of the test room using IES. It was found that the ventilation time of the day (that related to external temperatures), followed by the ventilation rates, had the biggest impact on the performance of a free running test room. These results were in line with Artmann et al., (2008) who assessed the effect of climate, thermal mass, heat gains, air change rates and heat transfer co-efficient on the effectiveness of night-time ventilation in several climates. They concluded that the ambient climatic conditions and the air flow rate during night-time ventilation mode were the most influential parameters. This highlighted the importance of using reliable weather files.

Additionally, modelling software-related input parameters, such as the pre-conditioning period, base internal temperature and time steps, were shown to have a significant impact on the modelling results of a naturally ventilated building. A preconditioning period of 30 days and one-minute time-steps were used for modelling naturally ventilated buildings due to the coupling of the airflow network with the thermal model.

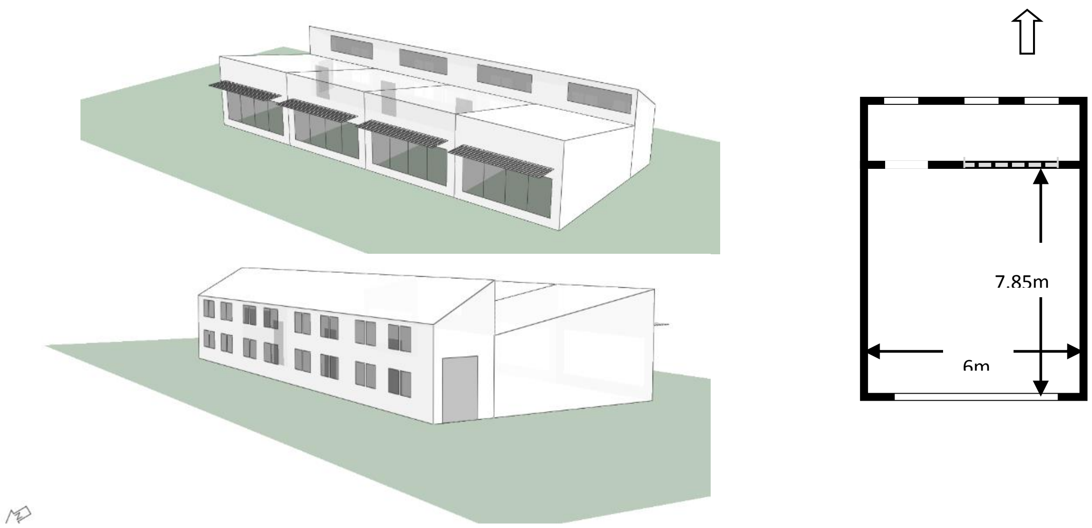


Figure 5.2: the preliminary test model

Table 5.1: constructions of the test room

Component	Material	Thickness (m)	Total U-value (W/m²K)	Notes
External walls	External rendering	0.02	0.9	
	Concrete block (medium)	0.15		
	Cavity	0.05		
	Concrete block (medium)	0.20		
	Gypsum plastering	0.02		
internal walls	Plaster	0.02	1.25	
	Concrete block (medium)	0.15		
	plaster	0.02		
Floor	Slate tiles	0.01	0.41	
	Tile bedding	0.01		
	Cast concrete (dense)	0.15		
	gravel	0.75		
Roof	External rendering	0.05	0.5	Pitched roof toward the north
	Polystyrene	0.04		
	Cast concrete	0.24		
	Plaster	0.02		
External glazing (south)	Low-e coated glass	0.006	1.97 (Aluminium frame)	Sliding windows (effective opening area is 50%-frame)
	cavity	0.006		
	Clear glass	0.006		
External glazing (north)	Clear glass	0.006	3.2 (Aluminium frame)	Bottom hung windows (openable angle 20°)
	cavity	0.006		
	Clear glass	0.006		
Internal glazing	Clear glass	0.004	3.55 (Aluminium frame)	Glass louvers

Table 5.2: internal gains

Profile	hours	gains	number
People	9:00-1200 13:00-17:00	90 W/person	15 people
Lighting	9:00-1200 13:00-17:00	10 W/m²	47.1 m²

5.4 Modelling of selected best practice buildings: Aqaba house (AH)

Preliminary modelling established broadly how a naturally ventilated room built using typical constructions in a hot arid location might perform, and what modelling-related input parameters might be most appropriate. Subsequent modelling of the selected best practice domestic buildings was undertaken to establish whether a 'well designed' building would perform as suggested by Givoni. Finally an uncertainty analysis was performed.

5.4.1 The model input data

Using IES Model IT, geometries of the house were constructed according to architectural plans provided by Visser 2013, Figure 5.3.

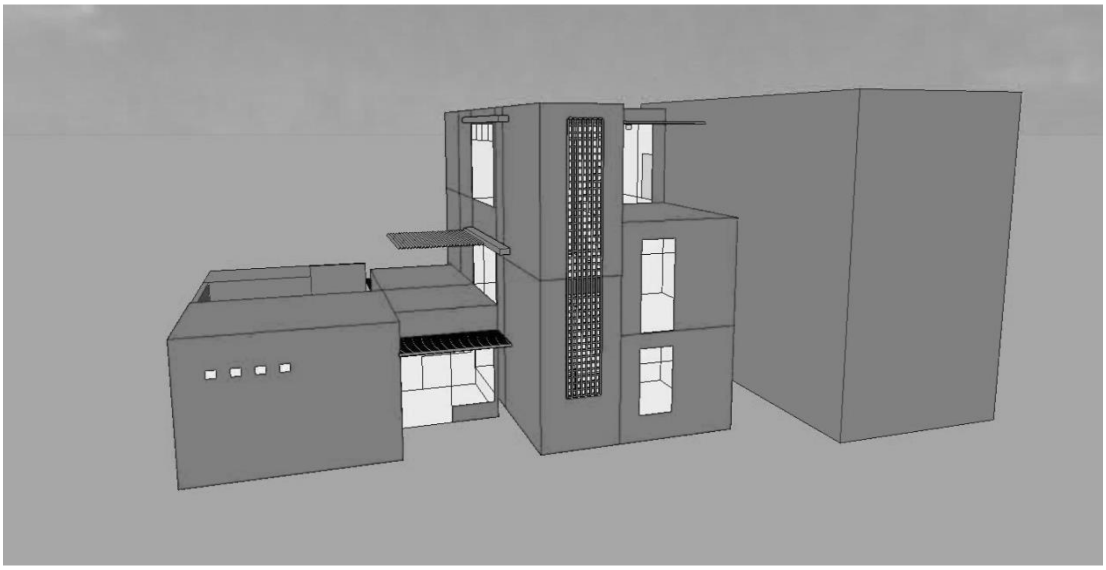


Figure 5.3: Aqaba house (AH) IES VE model

5.4.1.1. Building Element Construction details

The building element construction details were provided by the building architect (Visser, 2013). AH walls' U-value ranged between 0.3 and 0.5 W/m^2K (Rosenlund, 2010). Table 5.3, 5.5 and Figure 5.4 summarize the main characteristics of the materials used in AH. The materials were locally produced and no information or manufacturer's data were available to confirm the specifications provided by Visser. Therefore, these values were compared to CIBSE guide A (2006) and the IES materials database (Table 5.4) and were found to be within the range. Materials properties in Table 5.3 were used resulting in the thermal properties summarised in Table 5.5

Table 5.3: AH materials specifications used in the simulation

Material		Thermal Conductivity	Density	Specific heat Capacity
		W/mK	Kg/m^3	J/kgK
Concrete	Hollow Concrete block HCB normal	0.833	1300	1000
	HCB, Perlite aggregate	0.33	470	1000
	HCB, Volcanic aggregate	0.47	740	1000
	Cast Concrete	1.7	2200	840
	Reinforced concrete	1.9	2300	840
Plaster	Plaster with straw	0.5	1300	1000
Stone	Natural recycled stone	1.7	2200	840
tiles	ceramic floor tiles	1.3	2300	850
soil	sand	1.4	2100	650
	red soil	1.28	1460	880
insulation	mineral wool	0.036	20	710

	Material	Thickness	Frame	U-value	G-value
External windows	Clear Float	0.006	steel frames - no thermal breaks	3.11 W/m^{2}K	0.705
	Cavity	0.012			
	Clear Float	0.006			

Table 5.4: AH materials specifications as found in CIBSE guide A (2006) and IES data base.

Material	CIBSE guide A	Thermal Conductivity	Density	Specific Heat Capacity
		W/mK	Kg/m^3	J/kgK
Concrete	150mm HBC medium weight	0.62	1040	840
	150mm HBC light weight	0.48	880	840
	150mm Block with perlite light weight	0.33	1180	840
	150mm Block with perlite medium weight	0.39	1340	840
	concrete block dense protected	1.75	2300	1000
	cast concrete	1.33	2000	1000
	cast concrete dense	1.7	2200	840
	Reinforced concrete	1.9	2300	840
Plaster	cement lime plaster	0.8	1600	840
	plaster dense	0.57	1300	1000
Stone	sand stone	1.83	2200	710
tiles	ceramic	0.8	1700	850
soil	Soil: earth	1.28	1460	880
insulation	mineral wool	0.042	12	710
	mineral wool	0.036	24	710
	mineral wool	0.032	48	710
	IES data base			

Concrete	Concrete block light	0.19	600	1000
	Aerated concrete block	0.24	750	1000
	LW concrete block	0.38	609	837

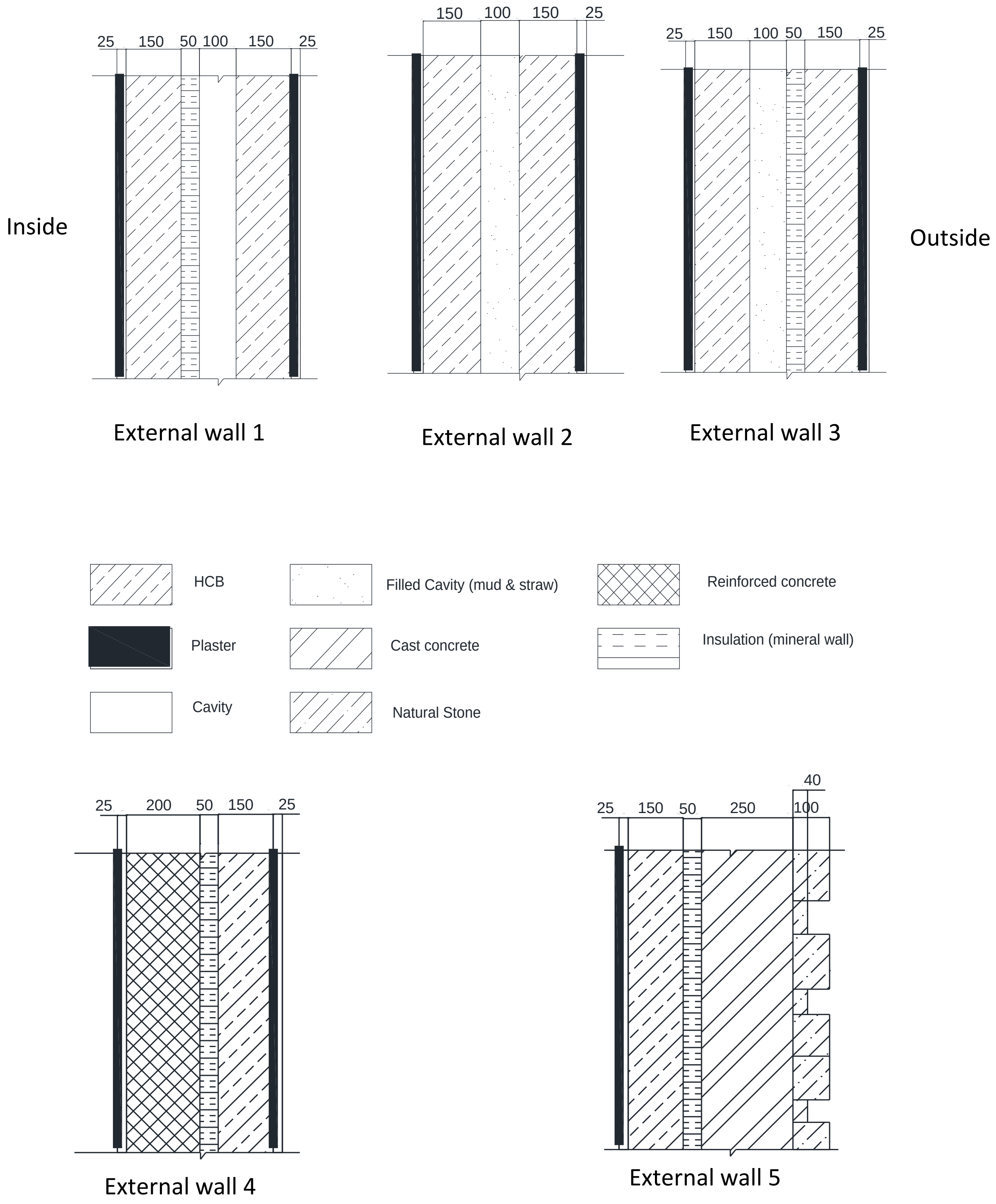


Figure 5.4: External wall constructions (dimensions in mm)

As could be noticed in the above tables, the concrete blocks used in Aqaba building were hollow concrete blocks (HCB). Wang et al., (2014) and Hatamipour et al., (2007) modelled buildings built of HCB using DSMs, in their studies HCB were represented through a single set of properties similarly to normal homogenous blocks. However, in Mohammad and Shea (2013), a variation of CIBSE combined method for calculating composite walls' U-value, was used in which HCB was represented as series of layers comprised of concrete and cavities. The correct representation of the complex structure of the HCB is beyond the scope of this study. It is understood that assuming a layered wall representation of the HBC could yield a more accurate representation of the U-value of the HCB, if its performance was the main interest of this work, and the precise nature and geometry of voids was known. However, this can result in the building performing in a manner not representative of its true thermal mass (more light weight). The main focus of this analysis is to assess the potential of natural ventilation in best practice buildings that are well insulated, thermally heavy and well shaded when compared to Givoni's prediction for similar buildings and therefore the HCB were modelled in IES VE using the values provided in table 5.3.

Table 5.5: AH construction elements thermal properties as calculated in IES (CIBSE method)

Element	U-value W/m²K	Thermal capacity Cm KJ/m²K	Admittance W/m²K	Decrement factor	Surface factor
External wall 1	0.36	67.75	3.6	0.303	0.71
External wall 2	0.35	67.75	3.24	0.068	0.73
External wall 3	0.93	88	3.7	0.139	0.65
External wall 4	0.44	177	5.12	0.108	0.44
External wall 5	0.5	67.75	4.17	0.081	0.67
Solid ground floor	0.2	154.5	3.31	0	0.68
roof	0.43	207	4.6	0.011	0.5
Green roof	0.17	207	4.7	0	0.5
internal wall	1.5	60.7	3.3	0.8	0.8
internal floor	1.4	186	4.5	0.066	0.51

External walls 2 & 3 in table 5.5 have a cavity filled with mud and straw (Figure 5.4) for which no information about its physical properties were provided by the architect. Thermal conductivities of 0.643 W/mK, densities of 1900 Kg/m^3 and specific heat capacities of 868 J/kgK for stabilised rammed earth in dry conditions (Allison & Hall, 2010) were used, resulting in U-values similar to those provided by Visser.

Based on the light colour of the walls; the walls' outside surface absorbance was assumed to be 0.3, inside surface as 0.2, inside and outside emissivity as 0.9.

The Venetian shutters were modelled in IES with transmission factors as presented in Table 5.6

Table 5.6: Transmission factors for the Venetian shutters

Transmission Factor at 15 degree increments

0	15	30	45	60	75	90
0.35	0.25	0.05	0.00	0.00	0.00	0.00

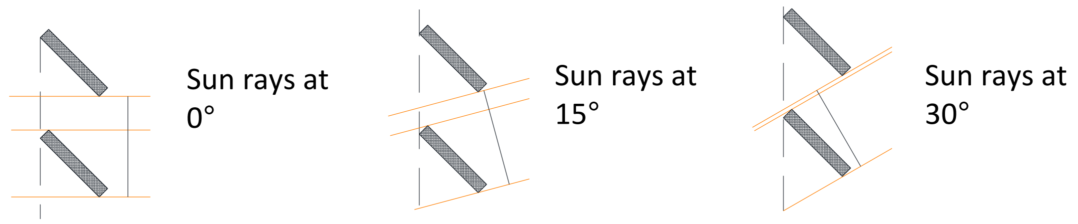


Figure 5.5: Transmission factor for external Venetian Shutters at 15 degree increments

5.4.1.2. Occupancy and building usage

Occupancy profiles were one of the input assumptions that would have the most significant impact on the modelling output (Andersen et al., 2009). A review of several studies by Blight and Coley (2013) suggested that energy consumption is more sensitive to occupant behaviour as the energy efficiency of the building improves. This is especially true in the residential sector where the number of the household occupants might vary every time the house changes ownership and the usage of appliances, lighting and other sources of internal gains will depend on the family's life style. Therefore, this aspect of modelling could be considered the most uncertain. Several studies made assumptions on the number of occupants based on the dwelling size and occupancy profiles were generated based on what was the norm, for example Hacker et al., (2008) assumed the house in their parametric study to be occupied by a family of three, one adult to be at home during the day, the child bedroom to be occupied from 20:00 to 07:00 and the parents' bedroom from 23:00 to 07:00.

Studies concerned mainly with diurnal occupancy generated typical profiles based on occupancy surveys, e.g. Duarte et al., (2013) generated occupancy profiles for offices based on occupancy monitoring data. Richardson et al., (2010) created a software program for generating occupancy and appliance-use profiles in dwellings based on the United Kingdom Time Use Survey data. This software was used by Blight and Coley, (2013), in their study on the sensitivity of energy consumption in Passivhaus dwellings to occupant behaviour. Similar time-use surveys such as the Harmonised European Time Use Survey that provided statistical data of people's use of time in 15 different European countries (Figure 5.7) can be used to generate or to make informed assumptions on diurnal occupancy profiles for different building types. Rakha et al., (2014) produced occupancy schedules based on activity-based travel surveys for Massachusetts, as shown in Figure 5.6

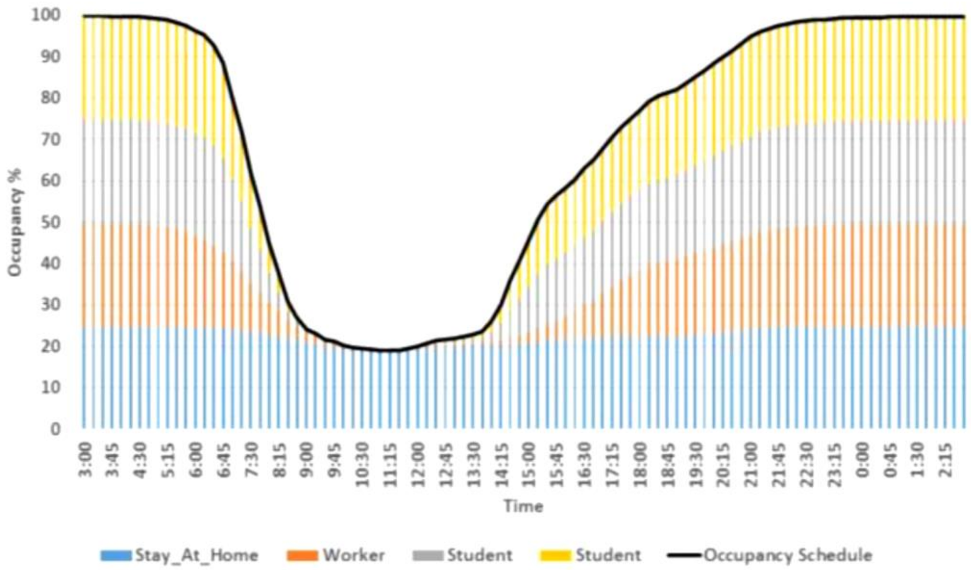


Figure 5.6: Single family house occupancy schedule (Rakha et al., 2014)

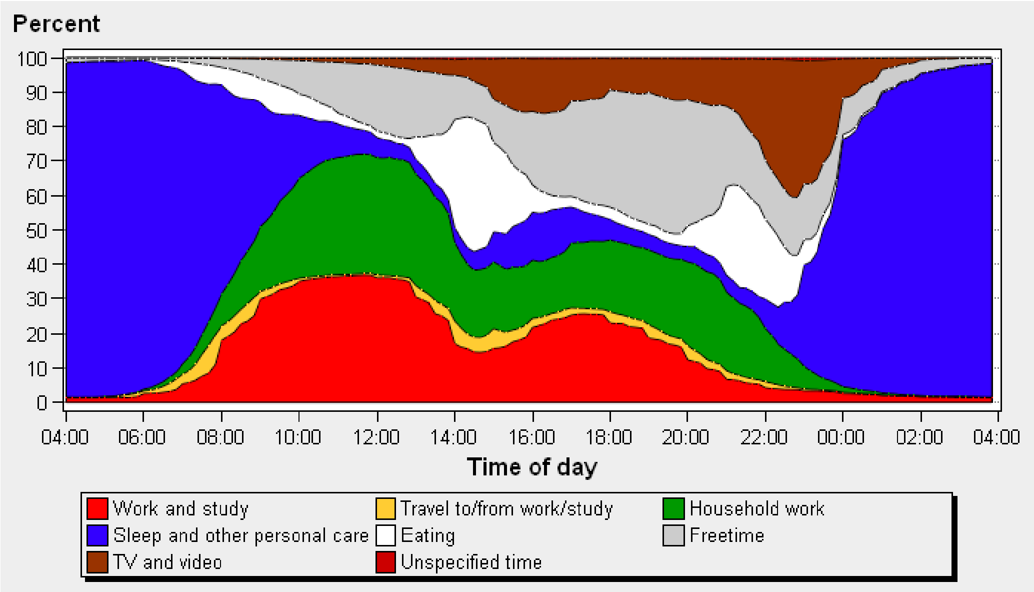


Figure 5.7: Illustration of time use during the day in Spain. Source: Harmonised European Time Use Survey

No similar time-use survey is available for the EM region, but one can use the information in Figure 5.7 for Spain in addition to information provided by the house owner to make informed decisions on the occupancy profile of the house. The house was occupied by a family of five from 2011 to 2013, but is currently unoccupied. It was fitted with energy efficient appliances and LED lighting. The house was assumed to be occupied by a family of 2 working adults and 3 school-age children. Sensible and latent heat gains from occupants were available from CIBSE Guide A, appliance heat gains were estimated where the appliance brand and annual energy consumption were known and compared to values found in Nadal et al., (2006), and Papadopoulos et al., (2008). For the purpose of this research the house was free running with no cooling, heating or mechanical ventilation systems in use. The window opening times were devised according to ventilation profiles summarised in table 5.7. Table 5.8 summarises occupancy and internal gain profiles.

Table 5.7: Ventilation profile

Ventilation mode	Aperture type	Ventilation time
Day time	External windows/doors	7:00 – 20:00
	Internal doors	Open continuously
Night time	External windows/doors	00:00 – 7:00, 22:00 – 00:00
	Internal doors	Open continuously
Day & night	External windows/doors	Open continuously
	Internal doors	Open continuously

Table 5.8: Occupancy and internal gains

Room	Occupancy	Source	Total heat gains (W)
Bedrooms	22:00 to 7:00	People	95 *1 or *2
	22:00 to 23:00	Laptop/PC	120
Living room	18:00-20:00/22:00	People	130 * 5
	18:00 to 22:00	TV set	120
	18:00 to 22:00	LED lighting	40
Kitchen	24/7	Fridge	50
	18:00 to 19:00	Oven	800
	17:00 to 19:00	People	145
	17:00 to 19:00	LED lighting	30
	20:00 to 21:00	Dish washer	200
Dining room	07:00 to 08:00	People	130 * 5
	19:00 to 20:00	People	130 * 5
	18:00 to 22:00	LED lighting	40

5.4.1.3 Other Input assumptions

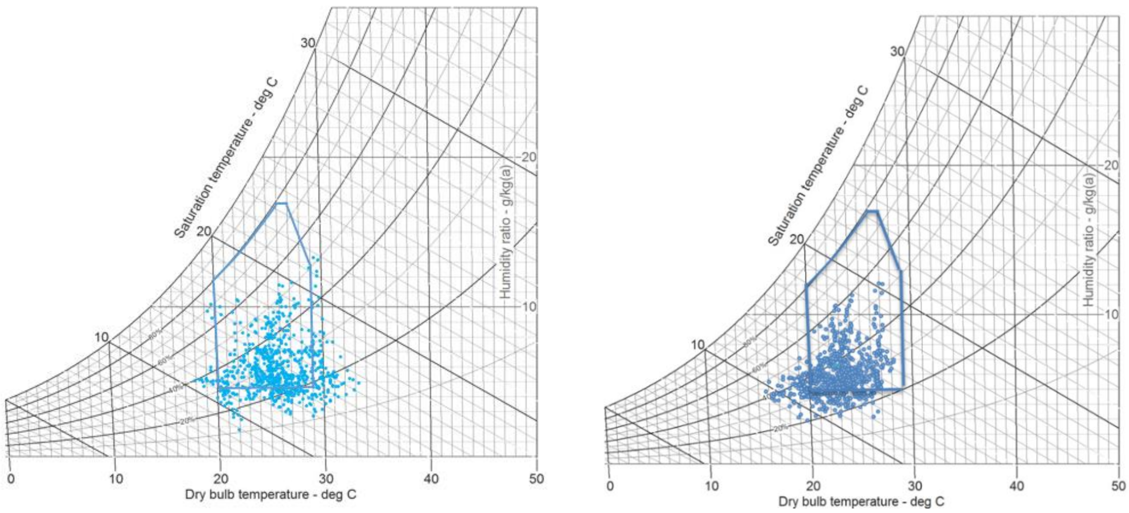
The building's air tightness is unknown as no pressure tests were carried out at any stage so an infiltration rate of 0.5 ach at ambient conditions was assumed in the base case. ASHRAE research showed that 75% of newly constructed homes had infiltration rates of between 0.25 and 0.75 air changes per hour (ASHRAE fundamentals 2005), similarly 0.5 ach was suggested as the infiltration rate of new built domestic buildings in Greece in study by Papadopoulos et al., 2008 in which a library of materials and constructions was created for Greece for use in DSM.

In addition, most windows had louvered Venetian shutters installed with insect meshes, which had an impact on the airflow rate through these windows, and constituted another input uncertainty. Louvered windows were chosen in IES to represent windows with Venetian shutters. The data inputs required were the openable area and the discharge coefficient C_D. The discharge coefficient relates to the volume flow rate through an orifice to its area and the applied pressure difference (Karave et al., 2007). Several parameters affect the C_D, namely, the opening area, wind speed, wind incident angle, and location of the opening in the façade (Karava et al., 2004). The discharge coefficient is usually taken as a constant value, approximately 0.6 to 0.65 for a sharp edged orifice such as a window (ASHRAE fundamentals 2009), manufacturers' data showed that the C_D of louvered ventilators ranged from 0.3 to 0.1 (Renson 2009; Architectural louvers 2007). However it was suggested that this was an over-simplification as it was influenced by dynamic factors such as wind direction (Karava et al., 2004; Chu et al., 2009). A value of C_D= 0.25 was chosen for the base case as it fell within the range found in manufacturers' data.

Both of these assumptions are evaluated later in a sensitivity analysis.

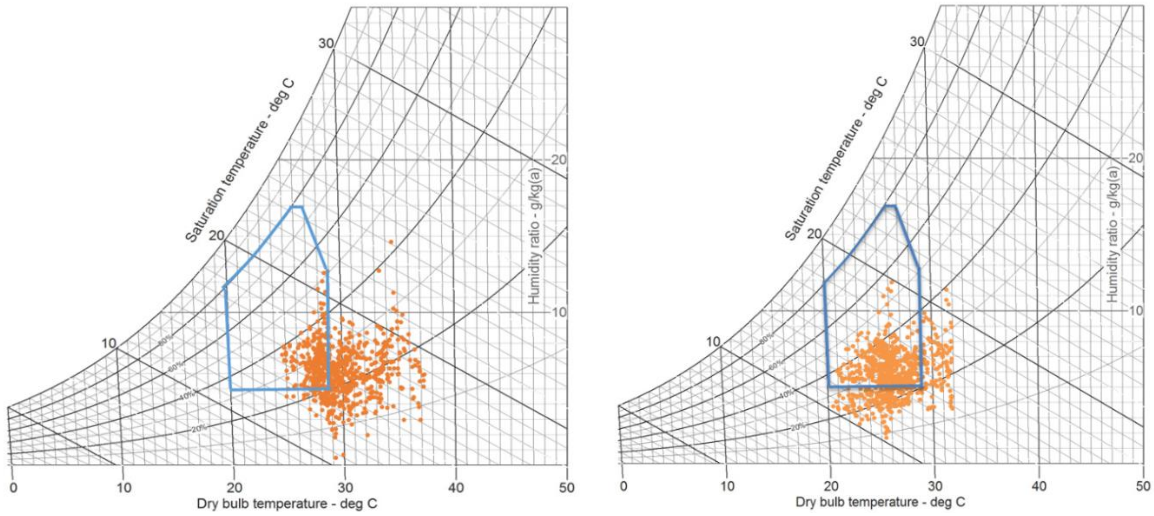
5.4.2 The results

In order to compare the building performance predicted by the model to the potential of passive strategies predicted by Givoni's BBCC that was established in Chapter 3, internal hourly temperatures and the corresponding moisture content for DTV and NTV were plotted on the psychometric chart with the comfort zone suggested by Givoni (Figures 5.8 to 5.14). The number of internal hours falling outside Givoni's suggested comfort zone were calculated and compared to the BBCC predictions. Then, due to doubt in the comfort zone suggested by Givoni discussed in Chapter 2, it was best to determine the potential of NTV and DTV using the comfort zones established in Chapter 3 (ASHRAE adaptive comfort equations). Therefore, the same analysis was repeated but using ASHRAE comfort zone.



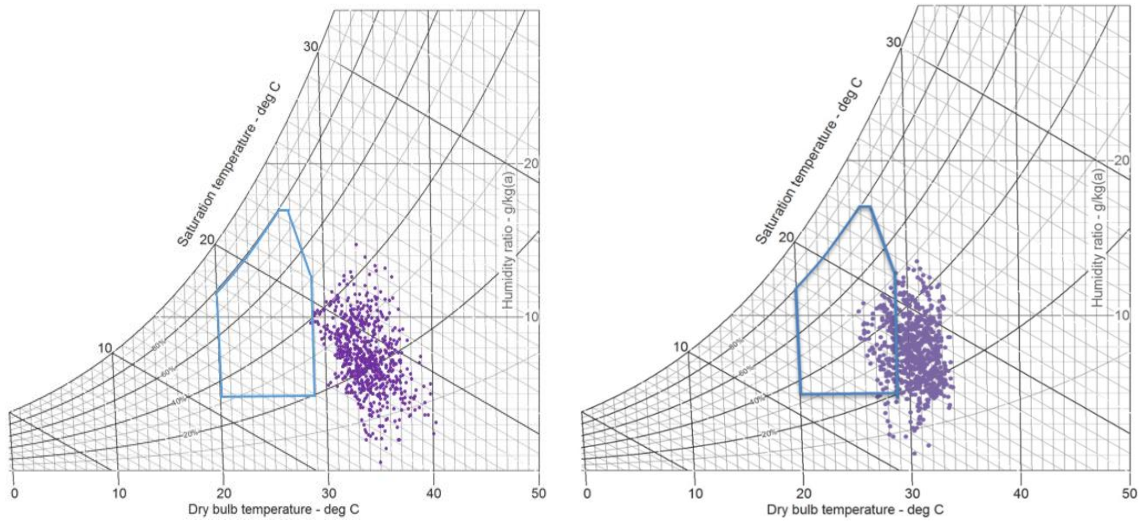
(a) (b)

Figure 5.8: AH internal operative temperatures in April, DTV (a); NTV (b).



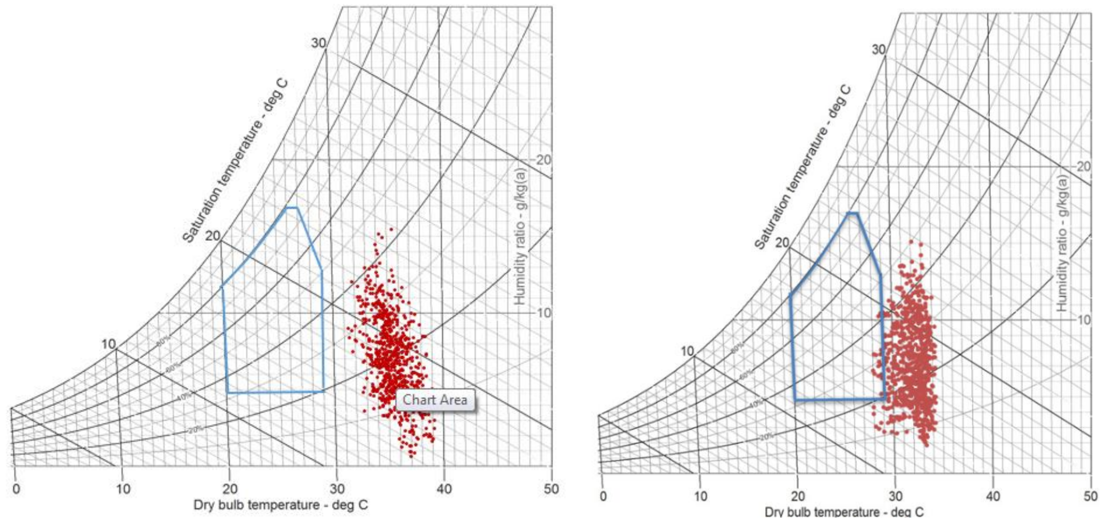
(a) (b)

Figure 5.9: AH internal operative temperatures in May, DTV (a); NTV (b)



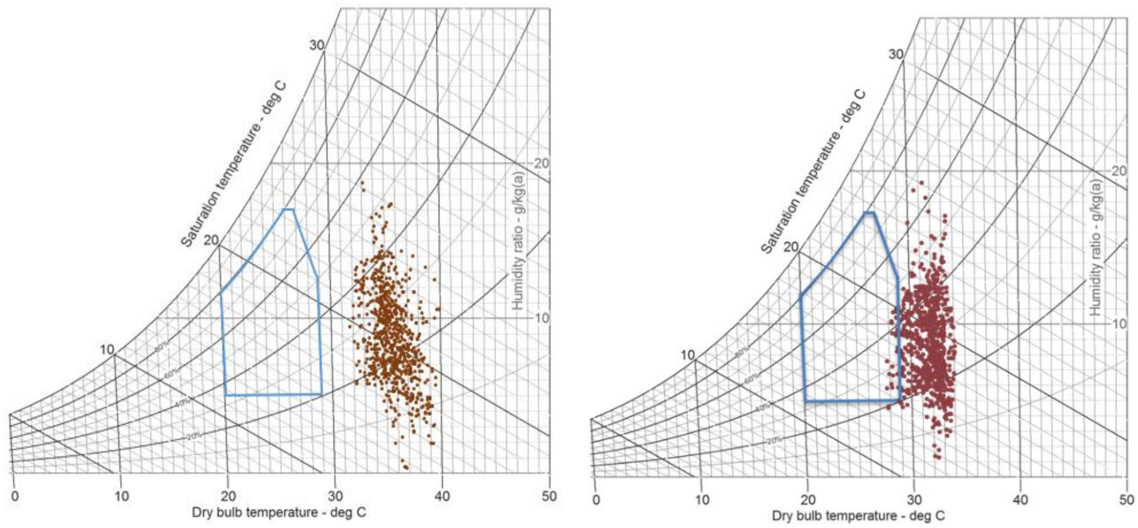
(a) (b)

Figure 5.10: AH internal operative temperatures in June, DTV (a); NTV (b).



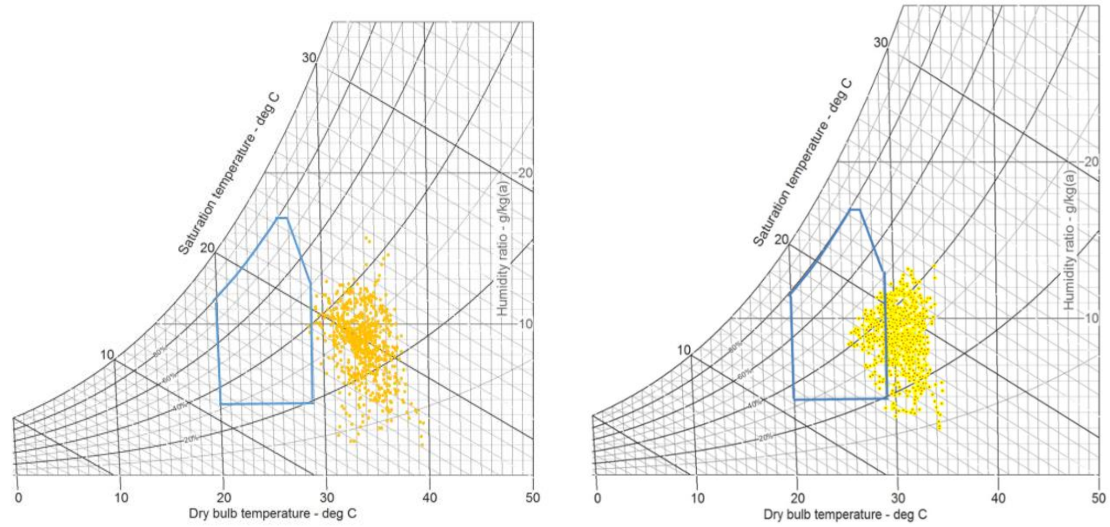
(a) (b)

Figure 5.11: AH internal operative temperatures in July, DTV (a); NTV (b).



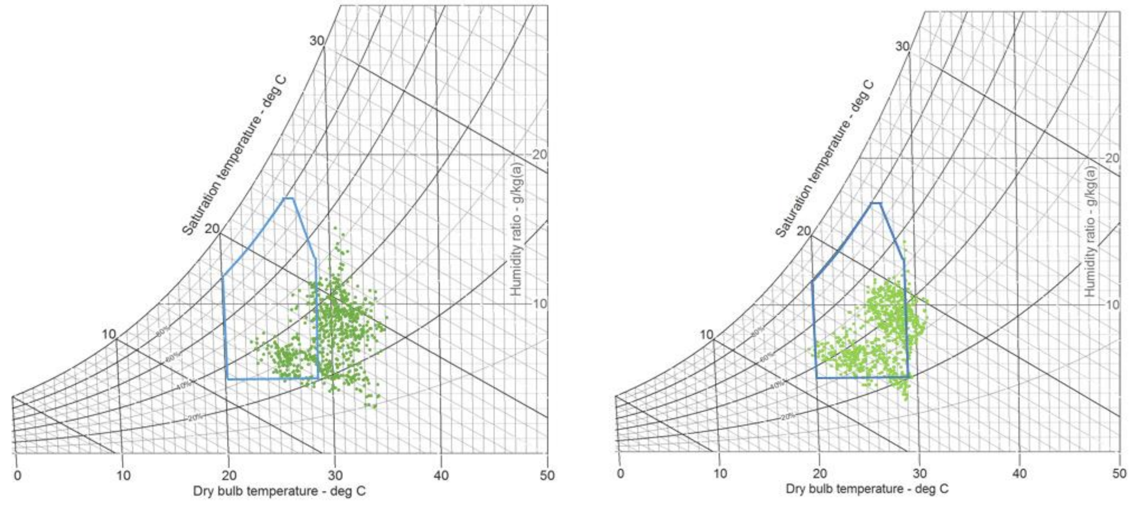
(a) (b)

Figure 5.12: AH internal operative temperatures in August, DTV (a); NTV (b).



(a) (b)

Figure 5.13: AH hourly internal operative temperatures in September, DTV (a); NTV (b).



(a) (b)

Figure 5.14: AH hourly internal operative temperatures in October, DTV (a); NTV (b).

The percentages of time in which the internal thermal conditions fell outside the comfort zone suggested by Givoni, and the comfort zone developed in Chapter 3 based on ASHRAE criteria, were calculated. They are presented in the following graphs as compared to the BBCC predictions based on external weather data established in Chapter 3 (Figures 5.15 & 5.16).

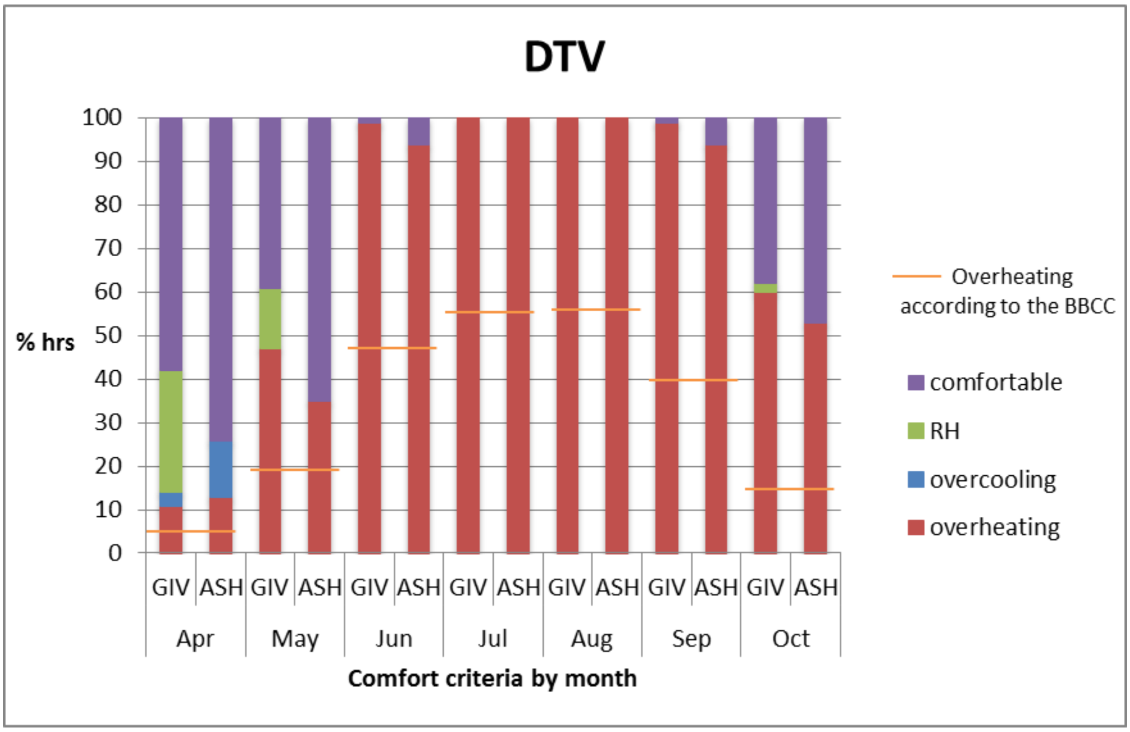


Figure 5.15: AH, DTV modelled potential based on Givoni's and ASHRAE comfort criteria, as compared to BBCC predictions, very hot and dry climate.

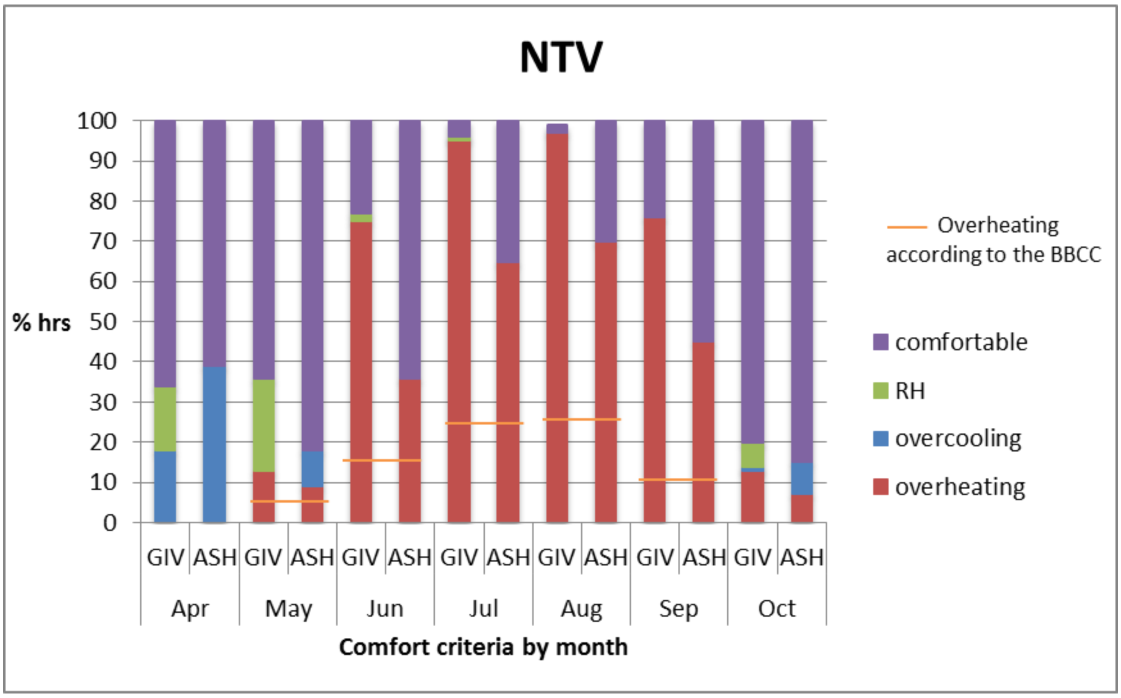


Figure 5.16: AH, NTV modelled potential based on Givoni's and ASHRAE comfort criteria, as compared to BBCC predictions, very hot and dry climate.

Two main conclusions could be drawn from this analysis, first that the choice of comfort zone had a significant effect on assessing the potential of natural ventilation in buildings. This was mainly because Givoni's suggested comfort zone was the same throughout the cooling season and across the EM region, while ASHRAE comfort zone varied from month to month and with location. This had consequently resulted in the variations observed in Figures 5.15 & 5.16 in the percentages of overheating/comfortable hours in each month between the two comfort zones. Additionally, while Givoni's comfort zone has a lower humidity limit, ASHRAE doesn't specify a lower limit, meaning that discomfort due to RH for the ASHRAE comfort zone was always the result of over-humid conditions (>80%). This is also true in all the subsequent analysis.

The second conclusion was that the BBCC significantly failed to predict the extent of over-heating hours for both DTV and NTV, especially in the hottest months. Overall, no potential of DTV and NTV for cooling in the very hot dry region was established, in that overheating of more than 60% of the time was observed in the two hottest months and more than 10% in 4 months. NTV can be recommended in cooler months (April and October), where less than 10% of hours exceeded the upper comfort limit of ASHRAE comfort zone, as seen in Figure

5.16. However, it should be noted that although NTV as a cooling strategy was successful in bringing temperatures down to below the upper comfort limit in cooler months, it often resulted in overcooling the building by a degree or two according to ASHRAE criteria.

5.5 Modelling of selected best practice buildings: Casa Batroun

5.5.1 The model input data

Using IES Model IT, geometries of the house were constructed according to architectural plans provided by Karkour (2013), Figure 5.17

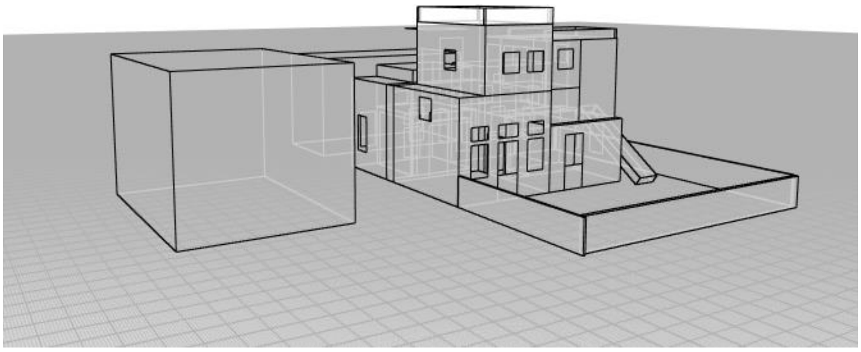


Figure 5.17: Casa Batroun model in IES VE

5.5.1.1. Constructions

The building construction details were provided by the building consultant, (Karkour, 2013). Chapter 4 described the selected building; Tables 5.9 and 5.10 summarizes the main characteristics of the materials used in Casa Batroun from materials catalogues (Guetex, 2011; Kronotherm, 2010; Schafwollmatte, 2010). When compared to values for similar materials in CIBSE guide A no significant discrepancies were found.

Casa Batroun consists of two separate flats that constitute completely separate envelopes. The ground floor is built of masonry and will be referred to as Casa Batroun Masonry (BM). The first floor is a timber construction and will be referred to as Casa Batroun Timber (BT).

Table 5.9: Casa Batroun materials

	Material	Thickness	Frame	U-value	G-value
External windows	Clear Float	0.004	Timber frames -no thermal breaks	2.8 W/m^2K	0.73
	Cavity	0.012			
	Clear Float	0.004			

Material		**Conductivity**	**Density**	**Specific heat Capacity**
		W/mK	Kg/m^3	J/kgK
Concrete	Cast concrete	1.3	2000	840
Timber	OSB	0.13	650	1700
	Plywood	0.12	540	1210
	Hardwood timber	0.14	720	1680
	Sand stone	3	2150	840
	Flooring screed	0.41	1200	1000
	Stone chippings	0.96	1800	1000
	Clay underfloor	1.5	1500	2085
Plaster	Clay plaster	0.91	1600	1000
Soil	Soil: clay or silt	1.28	1460	880
Insulation	Wood fibre- rigid	0.038	160	2100
	Wood fibre- loose	0.043	45	1380
	Sheep wool	0.042	15	1300

Table 5.10: Casa Batroun constructions thermal properties

Element	**U-value W/m^2K**	**Thermal capacity Cm KJ/m^2K**	**Admittance w/m^2k**	**Decrement factor**
External Masonry wall	0.45	32	2.48	0.308
External Timber wall	0.41	32	2.51	0.933
External Mezzanine wall	0.32	32	2.55	0.207
Solid ground floor	0.48	160	3.96	0
Roof	0.22	24.31	1.95	0.754
Green roof	0.27	24.31	1.66	0.709
Internal masonry wall	3.14	180	6.52	0.41
Internal timber wall	1.32	24.31	1.68	0.94
Internal floor	1.08	48.62	2.27	0.847

5.5.1.2 Occupancy and building usage

The house was separated into two flats: a one bedroom flat and a two bedroom flat. The house was generally used as a holiday house and the terraces and gardens were used as the living space rather than the living rooms (Karkour, 2013). According to information provided by the house owner, the following occupancy profiles were created.

Table 5.11: Occupancy and internal gains for Casa Batroun

BM	Occupancy	Source	Total heat gains (W)
Bedroom	23:00 to 08:00	People	95 * 1
Living room	08:00 to 09:00	People	130 * 1
	18:00 to 20:00	People	130 * 1
	18:00 to 20:00	PC	120
	18:00 to 22:00	LED lighting	30
Kitchen	24/7	Fridge	50
	18:00 to 19:00	Oven	800
	18:00 to 19:00	LED lighting	20
BT			
Bedroom 1	22:00 to 7:00	People	95 * 2
Bedroom 2	22:00 to 7:00	People	95 * 1
	20:00 to 22:00	Laptop/PC	120
Kitchen	24/7	Fridge	50
	18:00 to 19:00	Oven	800
	18:00 to 19:00	People	145
	18:00 to 19:00	LED lighting	30
Living room	07:00 to 08:00	People	130 * 3
	19:00 to 20:00	People	130 * 3
	18:00 to 22:00	LED lighting	40
	18:00 to 22:00	TV	120

Table 5.12: Ventilation profile for Casa Batroun

Ventilation mode	Aperture type	Ventilation time
Day time	External windows/doors	7:00 – 20:00
	Internal doors	Open continuously
Night time	External windows/doors	00:00 – 7:00, 21:00 – 00:00
	Internal doors	Open continuously
Day & night	External windows/doors	Open continuously
	Internal doors	Open continuously

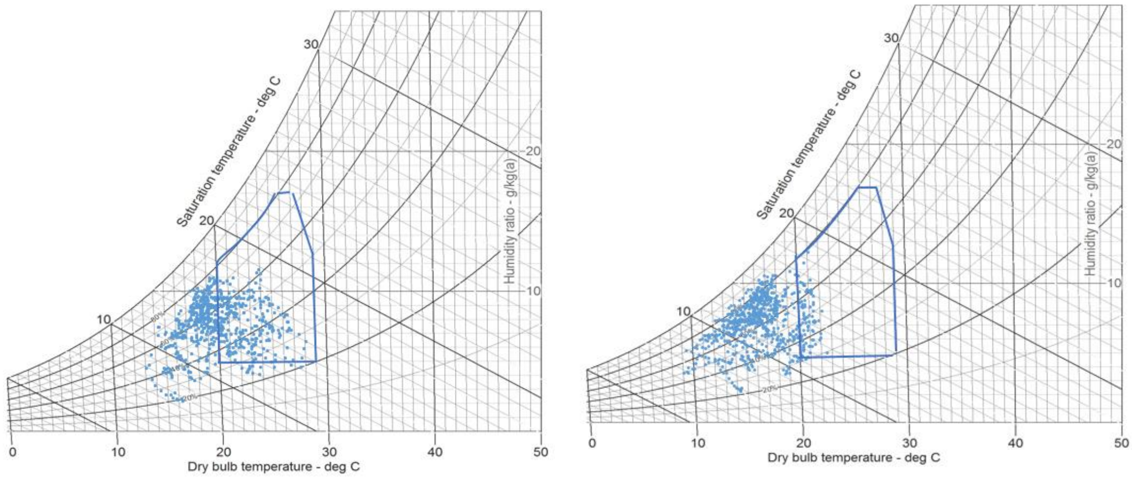
5.5.1.3 Other Input assumptions

The infiltration rate and the discharge coefficient of windows with insect meshes and Venetian shutters were also unknown. Similar assumptions to those in the AH were made so infiltration rate was assumed to be 0.5 ach and the discharge coefficient of windows was taken as 0.25.

5.5.2 Results

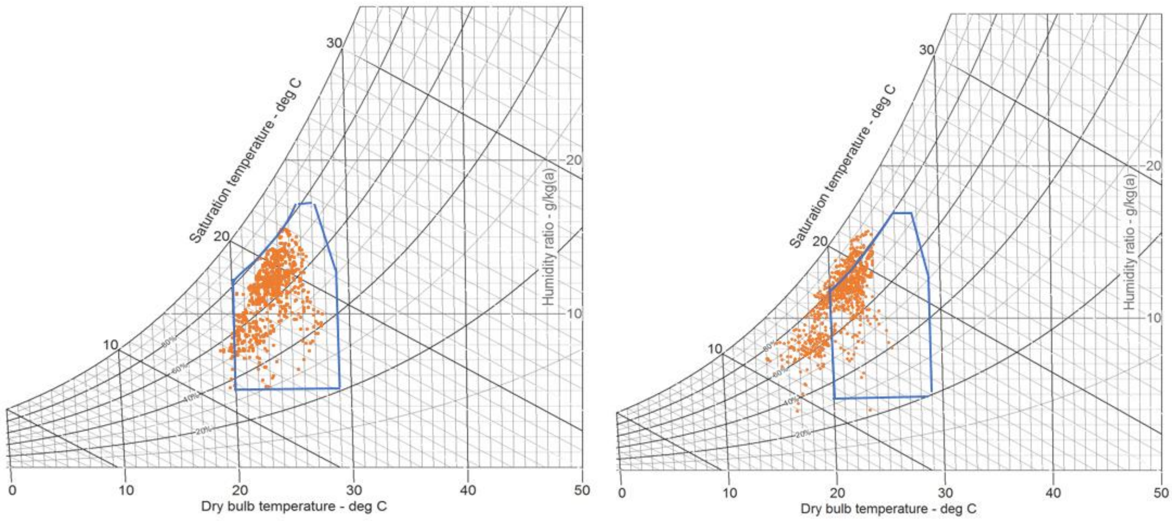
Initial simulations showed that there were significant variations in the resultant indoor temperatures across different rooms and levels. As Casa Batroun is comprised of two separate flats with completely different constructions each floor was analysed separately. Therefore two rooms were identified for further analysis, namely, L0R3 from the ground floor BM and L1R3 from the first floor BT. Both rooms function as living rooms with relatively similar internal heat gains but with different orientations and constructions. The hourly operative temperatures for L0R3 and the corresponding moisture content were plotted on the Psychometric chart and the Givoni comfort zone was indicated, Figures 5.18 to 5.24. The same was done for L1R3 and shown in Figures 5.25 to 5.31, and then repeated using ASHRAE comfort zone. A summary of the percentage of times of comfortable and uncomfortable hours according to of Givoni's and ASHRAE's comfort zones are presented in figures 5.31 to 5.34

Room L0R3 BM:



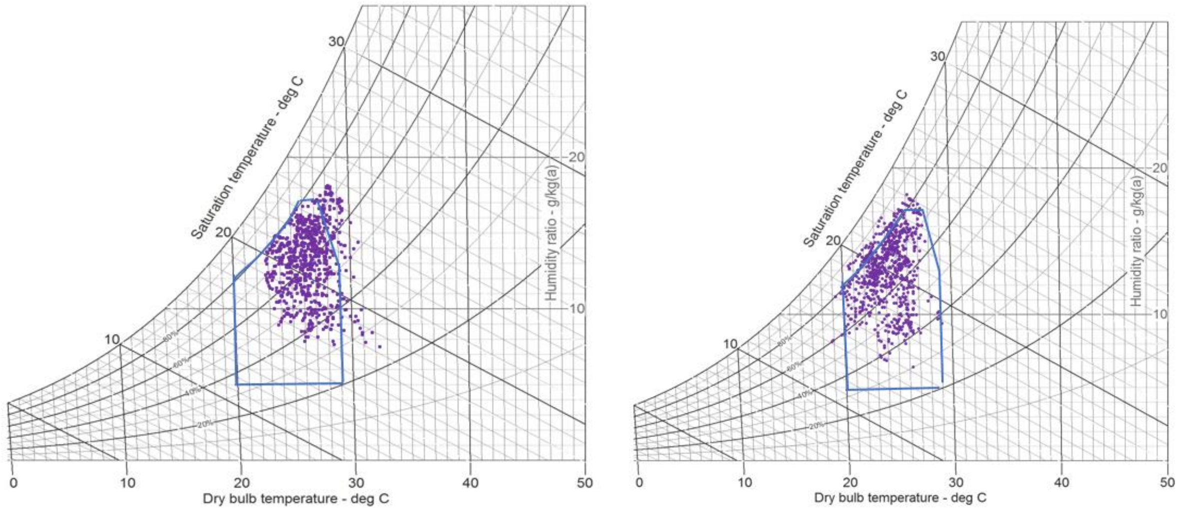
(a) (b)

Figure 5.18: Casa Batroun L0R3 hourly internal operative temperatures in April, DTV (a); NTV (b).



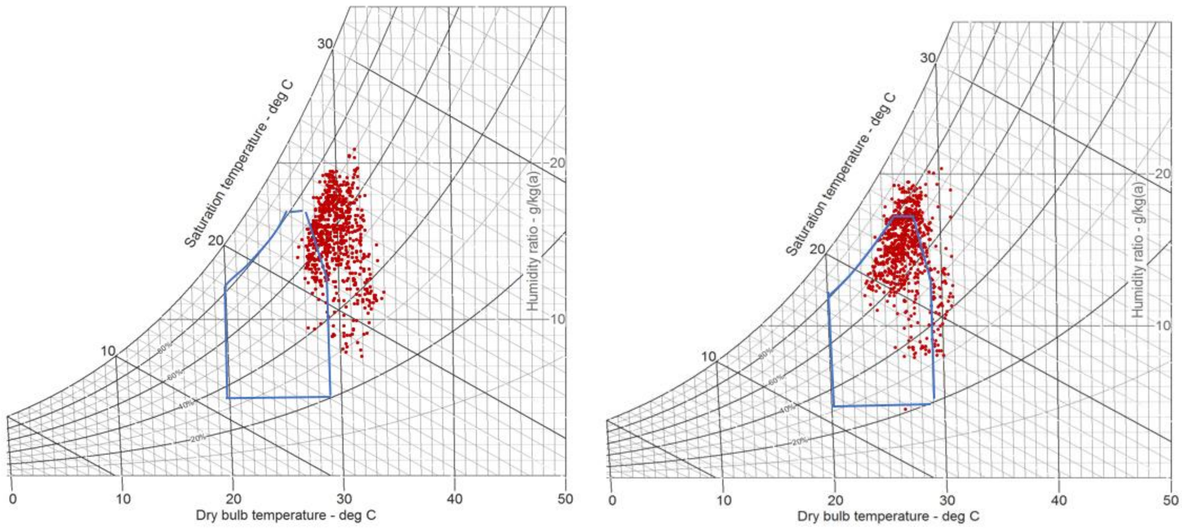
(a) (b)

Figure 5.19: Casa Batroun L0R3 hourly internal operative temperatures in May, DTV (a); NTV (b).



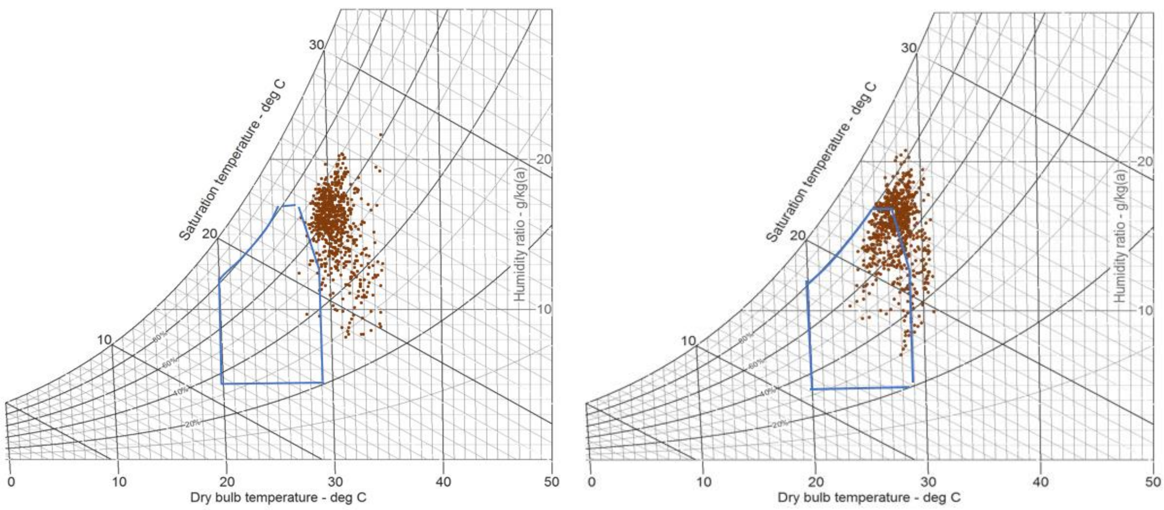
(a) (b)

Figure 5.20: Casa Batroun L0R3 hourly internal operative temperatures in June, DTV (a); NTV (b).



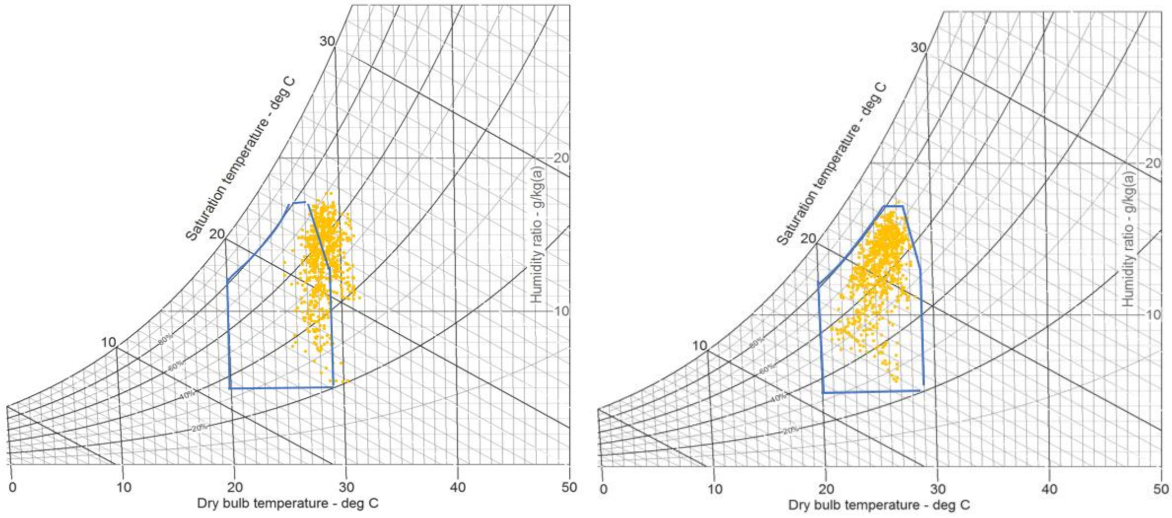
(a) (b)

Figure 5.21: Casa Batroun L0R3 hourly internal operative temperatures in July, DTV (a); NTV (b).



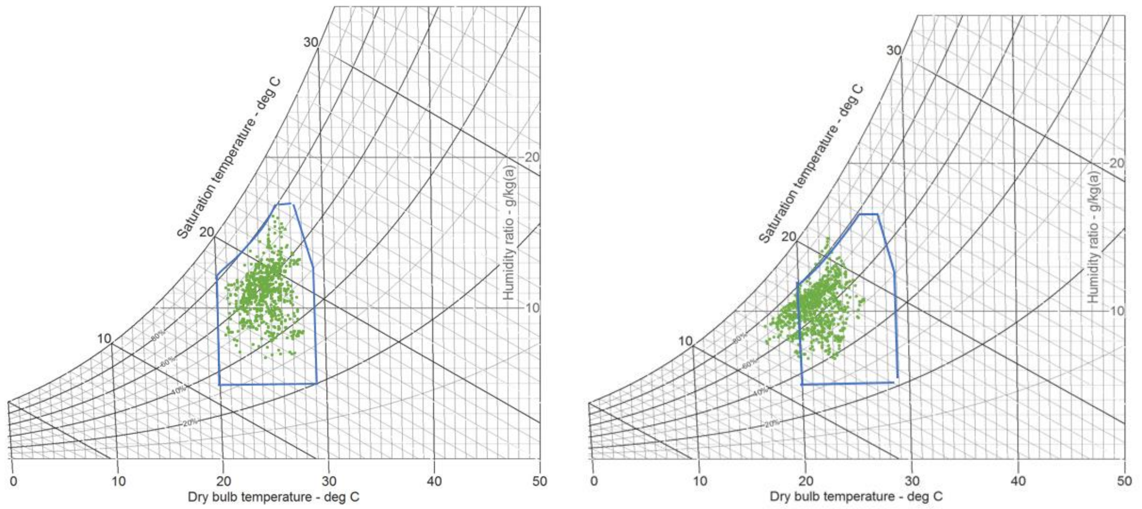
(a) (b)

Figure 5.22: Casa Batroun L0R3 hourly internal operative temperatures in August, DTV (a); NTV (b).



(a) (b)

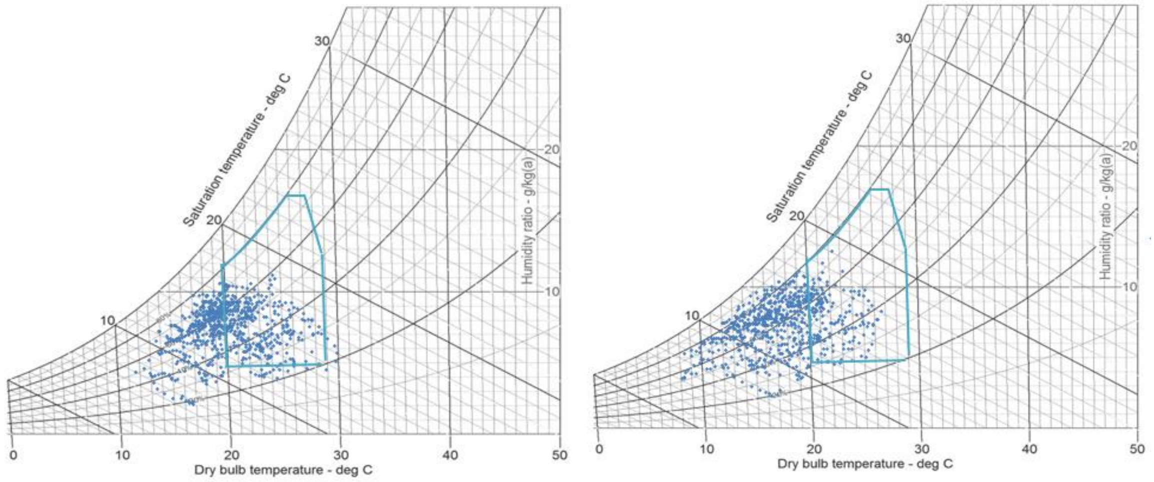
Figure 5.23: Casa Batroun L0R3 hourly internal operative temperatures in September, DTV (a); NTV (b).



(a) (b)

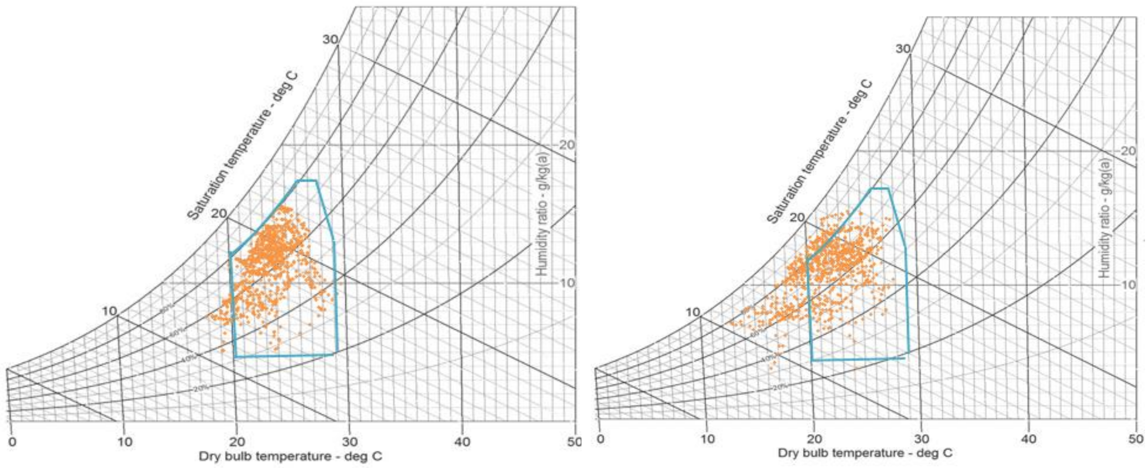
Figure 5.24: Casa Batroun L0R3 hourly internal operative temperatures in October, DTV (a); NTV (b).

Room L1R3 BT:



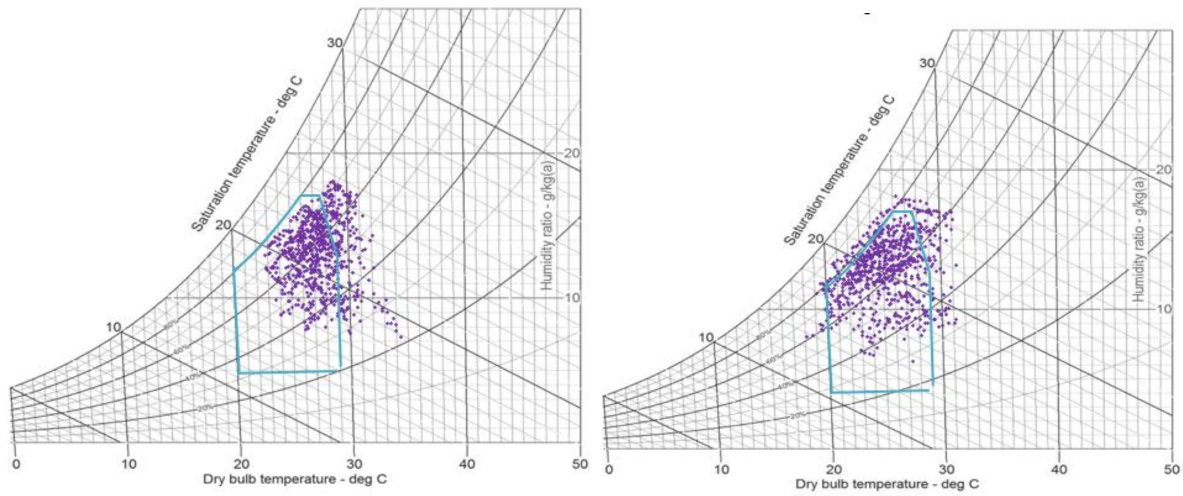
(a) (b)

Figure 5.25: Casa Batroun L1R3 hourly internal operative temperatures in April, DTV (a); NTV (b).



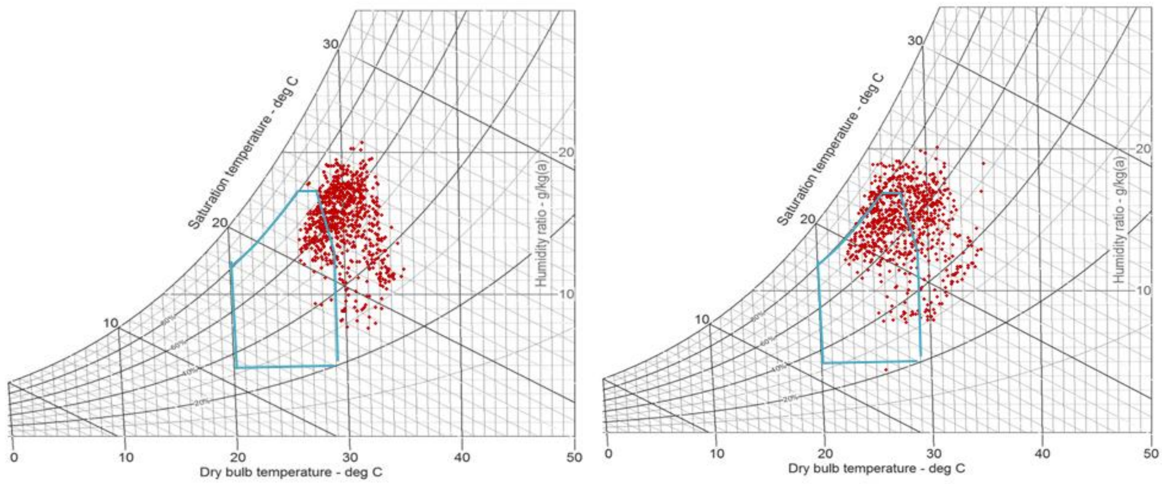
(a) (b)

Figure 5.26: Casa Batroun L1R3 hourly internal operative temperatures in May, DTV (a); NTV (b).



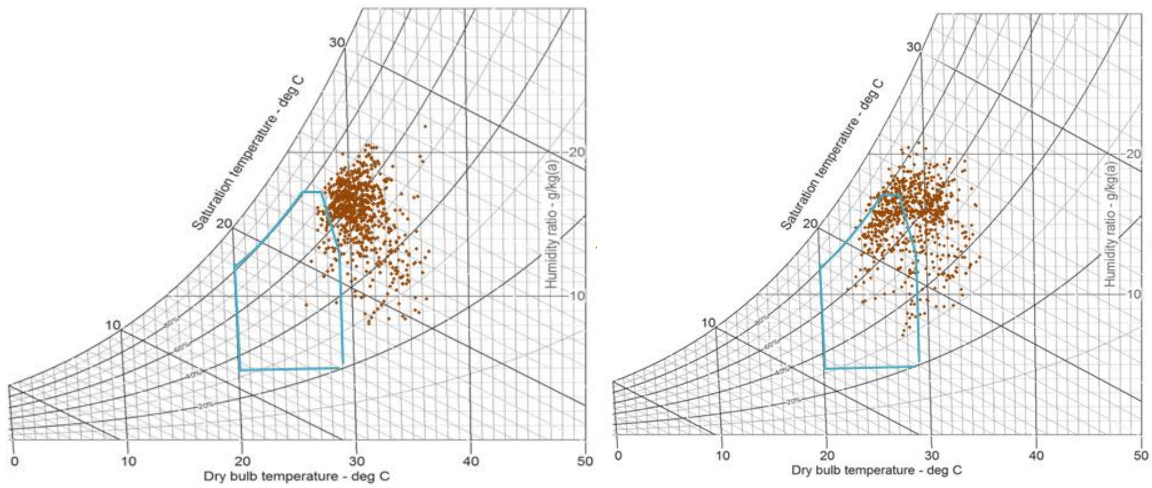
(a) (b)

Figure 5.27: Casa Batroun L1R3 hourly internal operative temperatures in June, DTV (a); NTV (b).



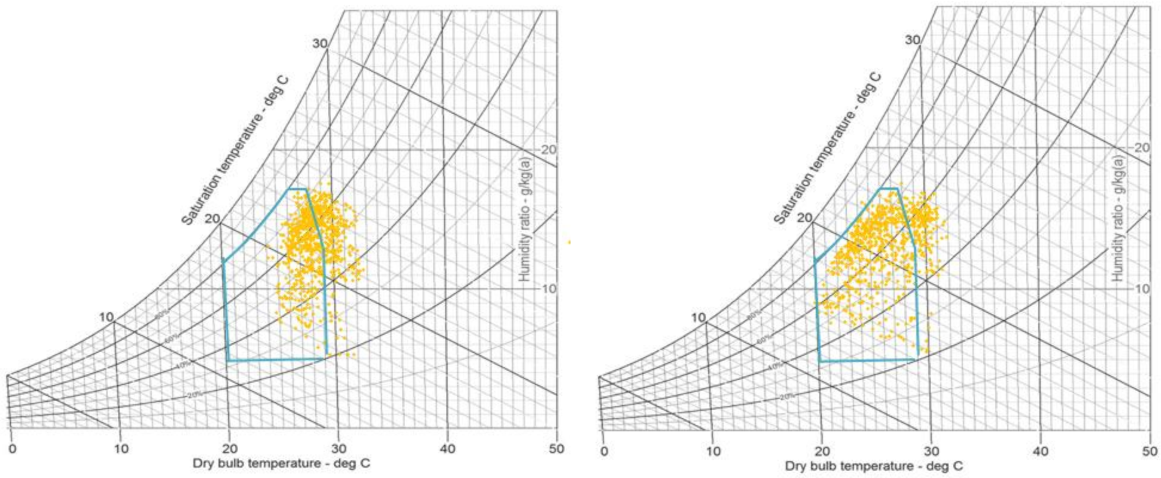
(a) (b)

Figure 5.28: Casa Batroun L1R3 hourly internal operative temperatures in July, DTV (a); NTV (b).



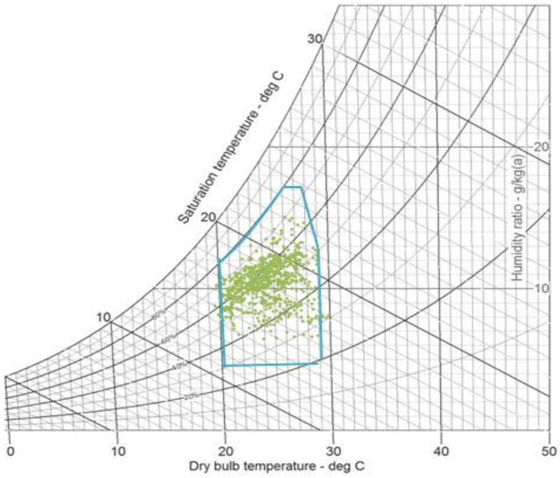
(a) (b)

Figure 5.29: Casa Batroun L1R3 hourly internal operative temperatures in August, DTV (a); NTV (b).



(a) (b)

Figure 5.30: Casa Batroun L1R3 hourly internal operative temperatures in September, DTV (a); NTV (b).



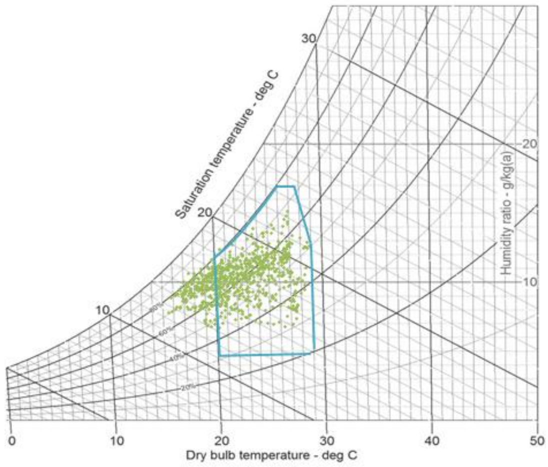


Figure 5.31: Casa Batroun L1R3 hourly internal operative temperatures in October, DTV (a); NTV (b).

Similarly to the results of Aqaba house, the choice of comfort criteria had a significant impact on the modelling predictions. Additionally, the BBCC failed again to predict the extent of overheating according to their own comfort criteria, whereas the gap between the BBCC predictions and the modelling results for ASHRAE comfort zone was of less magnitude for DTV. Moreover, BT overheated by 5 to 12% more hours than BM.

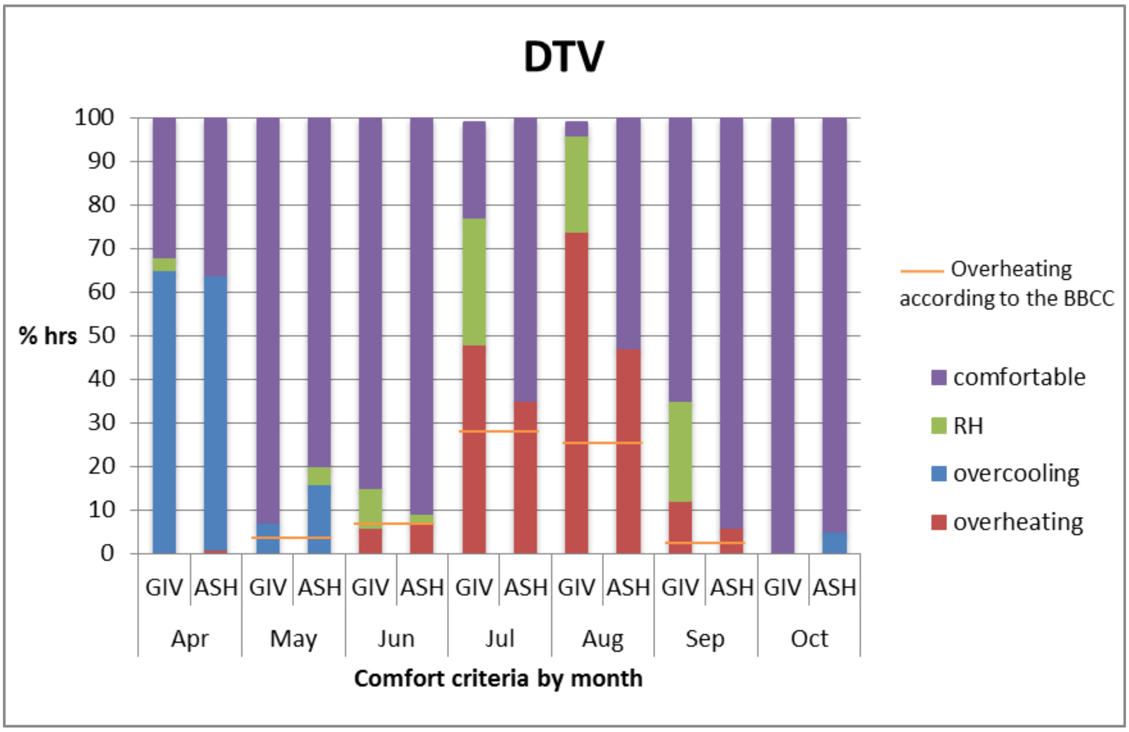


Figure 5.32: DTV modelling potential in BM based on Givoni's and ASHRAE comfort criteria, as compared to BBCC predictions, hot humid region

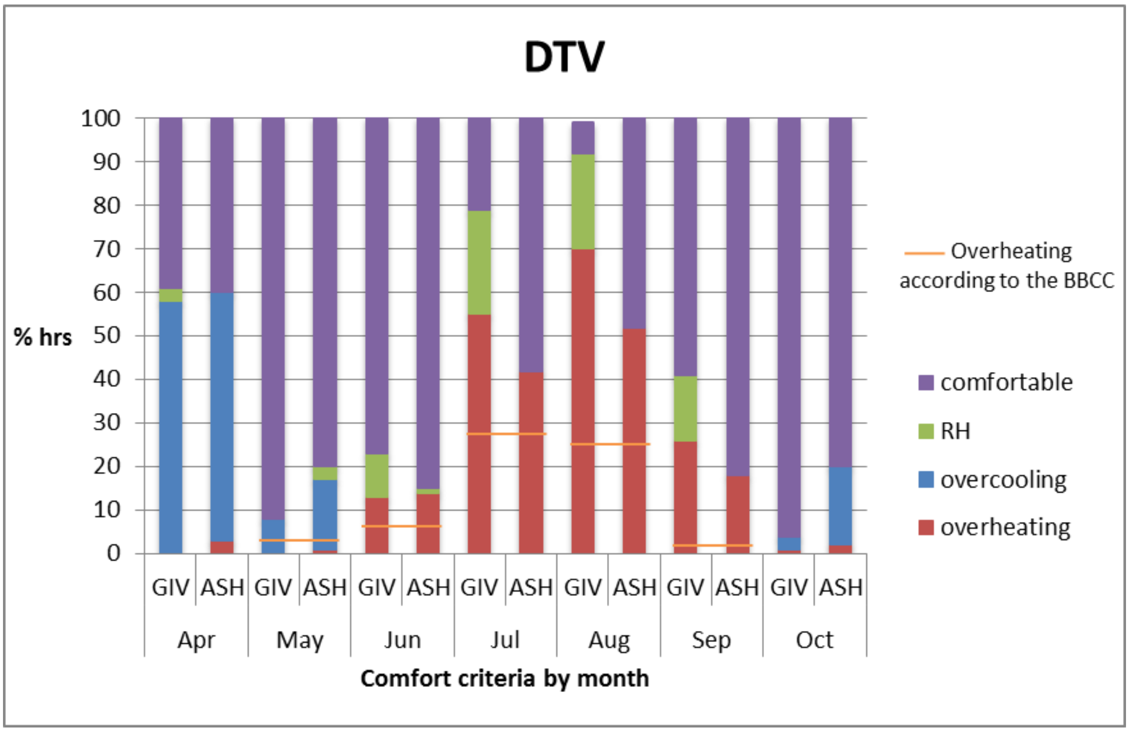


Figure 5.33: DTV modelling potential in BT based on Givoni's and ASHRAE comfort criteria, as compared to BBCC predictions, hot humid region

Contrary to DTV, the modelling of Casa Batroun for NTV showed that the BBCC over predicted the number of overheating hours for BM, while again under-predicted it in BT.

This illustrate the significance of the influence construction materials have on night ventilation potential. Figure 5.34 & 5.35

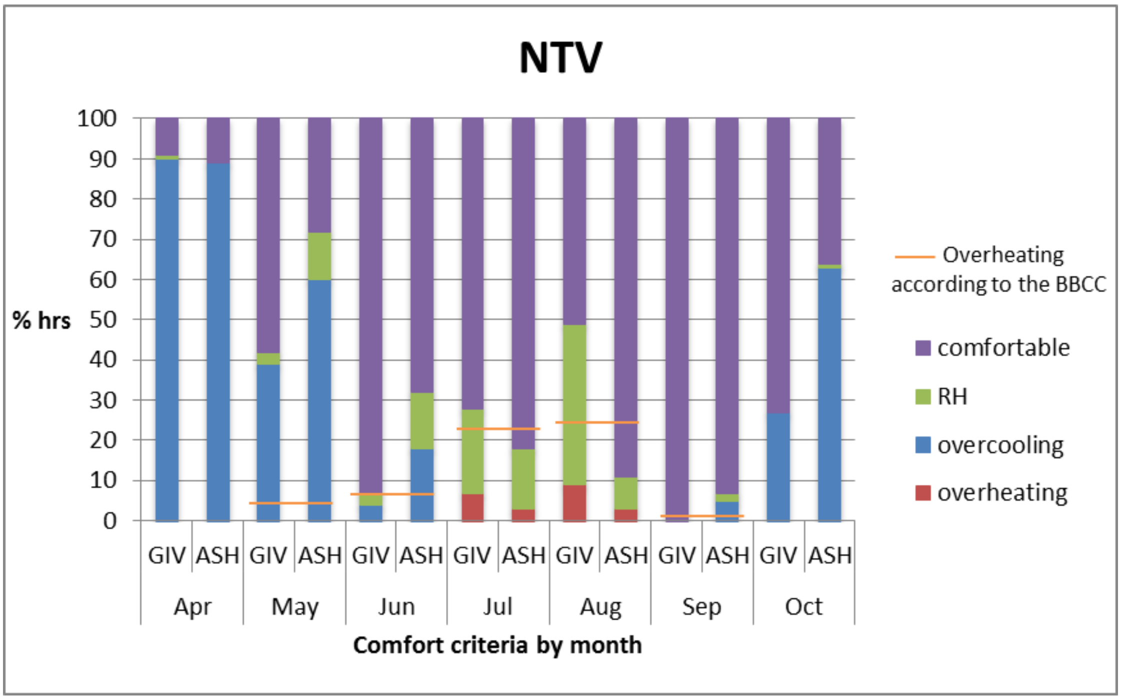


Figure 5.34: NTV modelling potential in BM based on Givoni's and ASHRAE comfort criteria, as compared to BBCC predictions, hot humid region

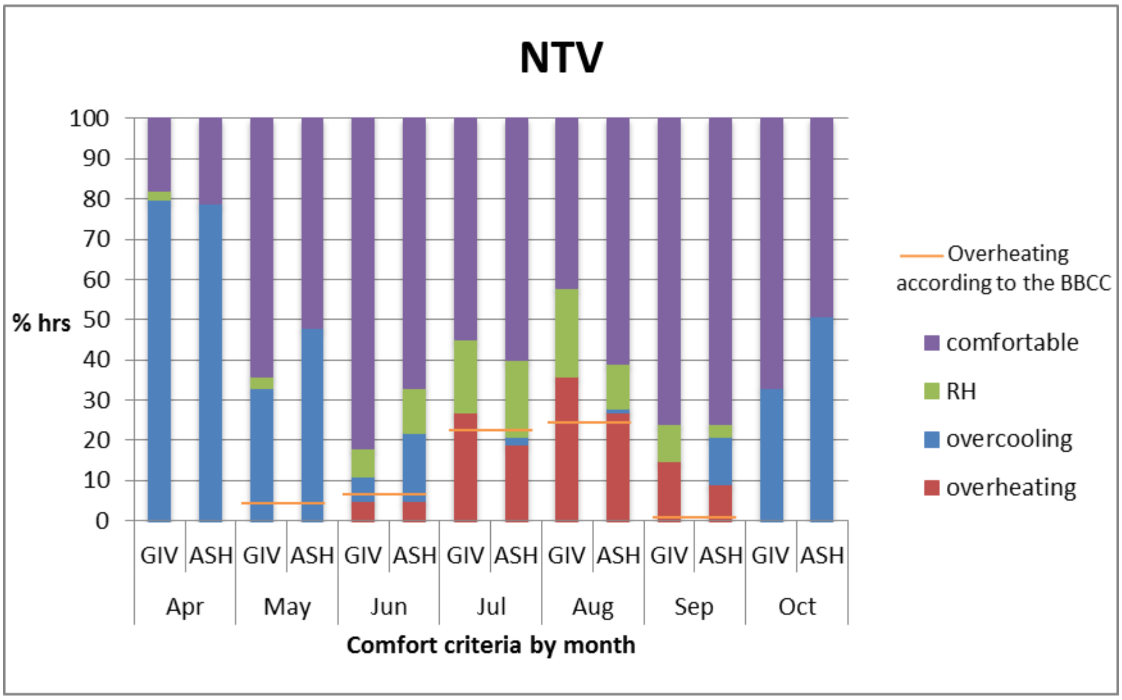


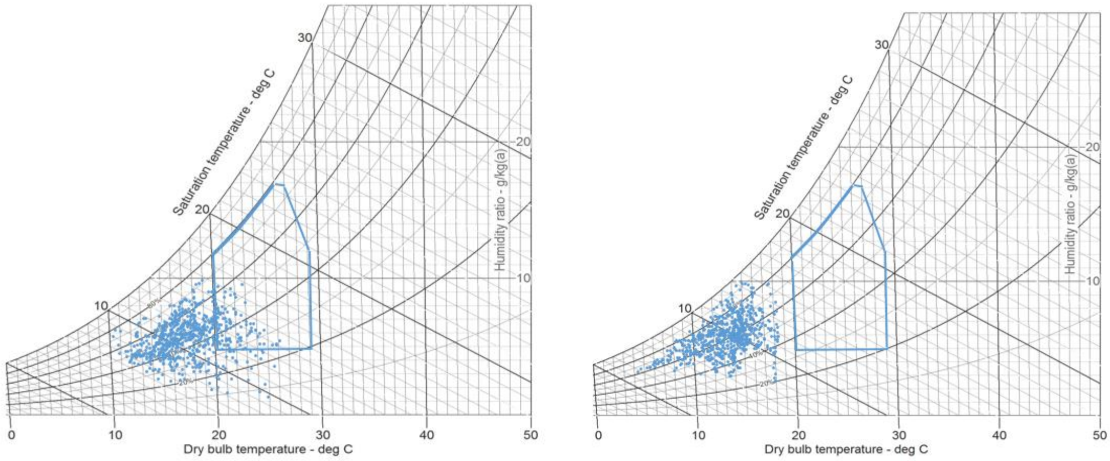
Figure 5.35: NTV modelling potential in BT based on Givoni's and ASHRAE comfort criteria, as compared to BBCC predictions, hot humid region

It could be concluded that DTV is beneficial and a sufficient comfort strategy from April to June and September to October, regardless of the construction type. NTV is recommended for the hottest months (July and August) only if combined with sufficient thermal mass as it resulted in less than 5% overheating hours. Nonetheless, high humidity levels remain a source of discomfort in those hot months and an additional dehumidification strategy is required.

5.6 Modelling of selected best practice buildings: Damascus

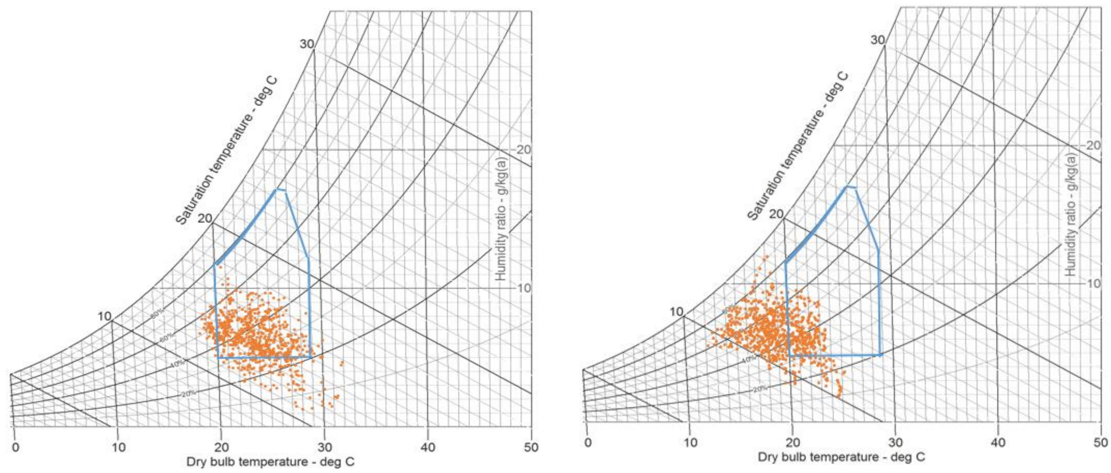
Given that no exemplars of best practice exist in the hot-dry region, both houses, AH and Casa Batroun BM & BT, were modelled again using the Damascus weather file (IWEC).

The results of modelling AH using Damascus weather showed a combination of either daytime or night-time ventilation was sufficient to maintain comfort throughout the cooling season. The cooling season however started later than in the very hot dry region. As the weather in April was still cool, neither strategy is recommended, in fact heating might still be required. In May NTV was not recommended because it over-cooled the building, similarly in October, DTV would suffice. In the hot months of June, July and August, NTV could sustain comfort and in September both DTV and NTV were acceptable strategies. However, NTV resulted in over cooling for 20% of the time. Figures 5.36 to 5.42 show the hourly internal temperatures for the Aqaba house modelled using the Damascus weather file.



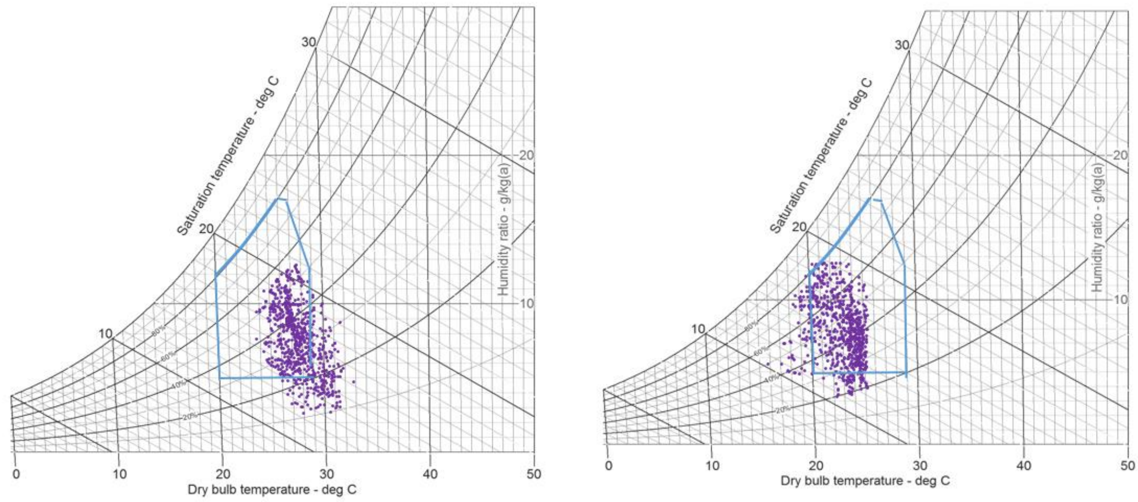
(a) (b)

Figure 5.36: AH for Damascus hourly internal operative temperatures in April, DTV (a); NTV (b).



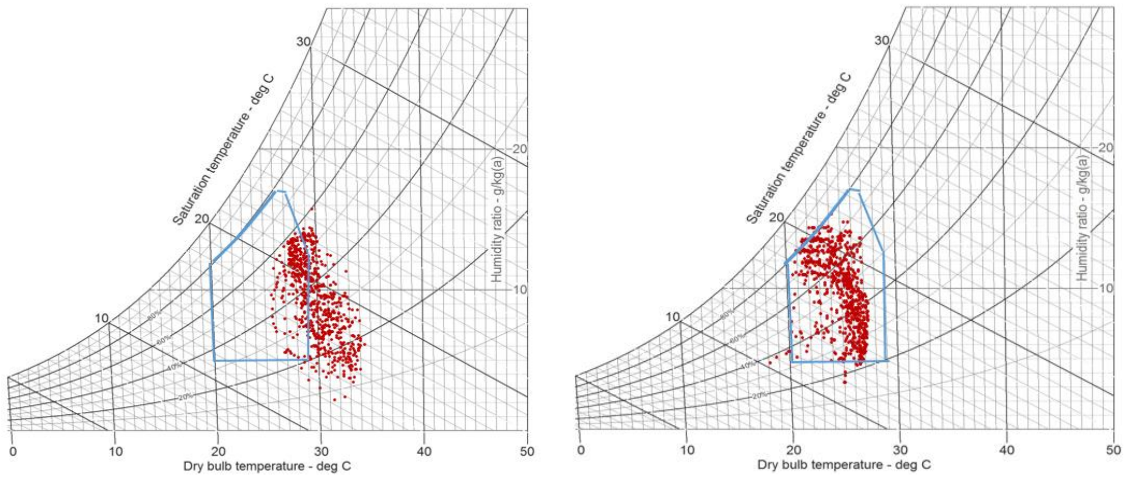
(a) (b)

Figure 5.37: AH for Damascus hourly internal operative temperatures in May, DTV (a); NTV (b).



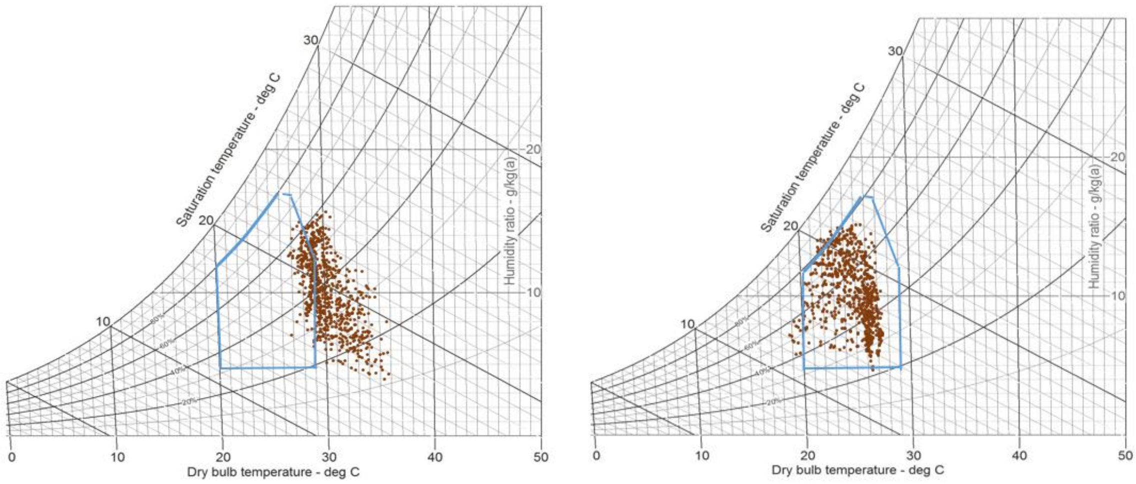
(a) (b)

Figure 5.38: AH for Damascus hourly internal operative temperatures in June, DTV (a); NTV (b).



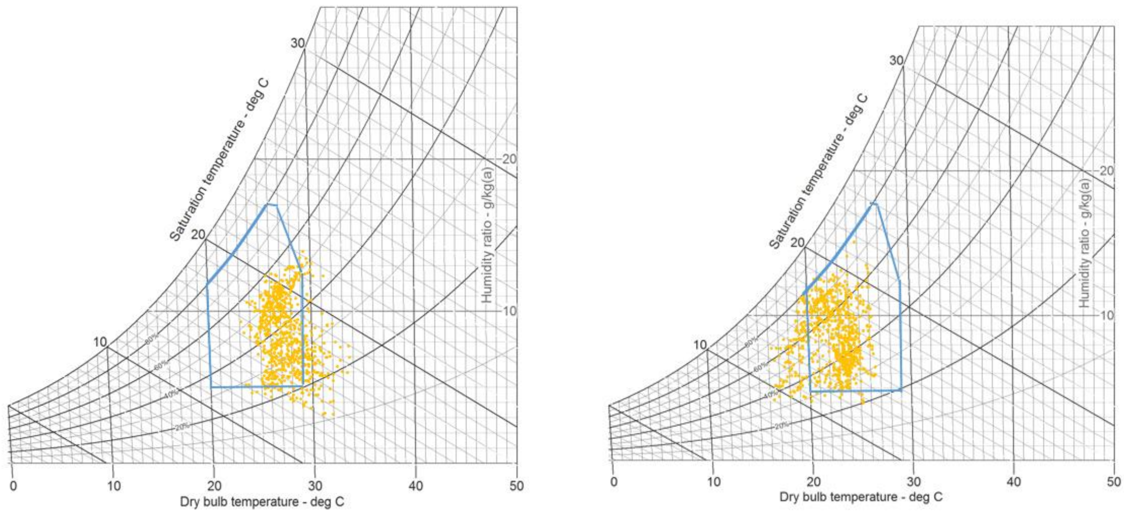
(a) (b)

Figure 5.39: AH for Damascus hourly internal operative temperatures in July, DTV (a); NTV (b).



(a) (b)

Figure 5.40: AH for Damascus hourly internal operative temperatures in August, DTV (a); NTV (b).



(a) (b)

Figure 5.41: AH for Damascus hourly internal operative temperatures in September, DTV (a); NTV (b).

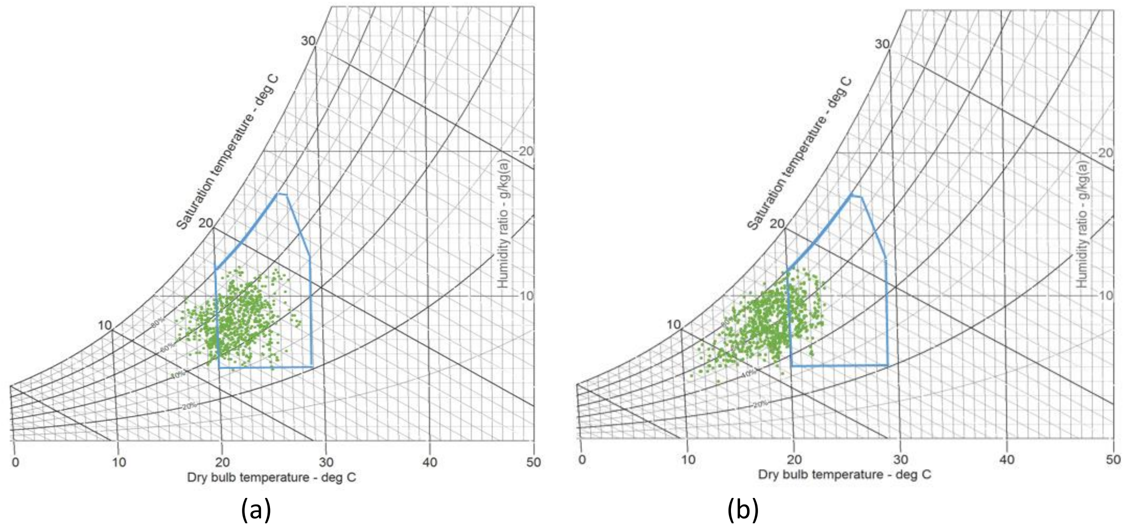


Figure 5.42: AH for Damascus hourly internal operative temperatures in October, DTV (a); NTV (b).

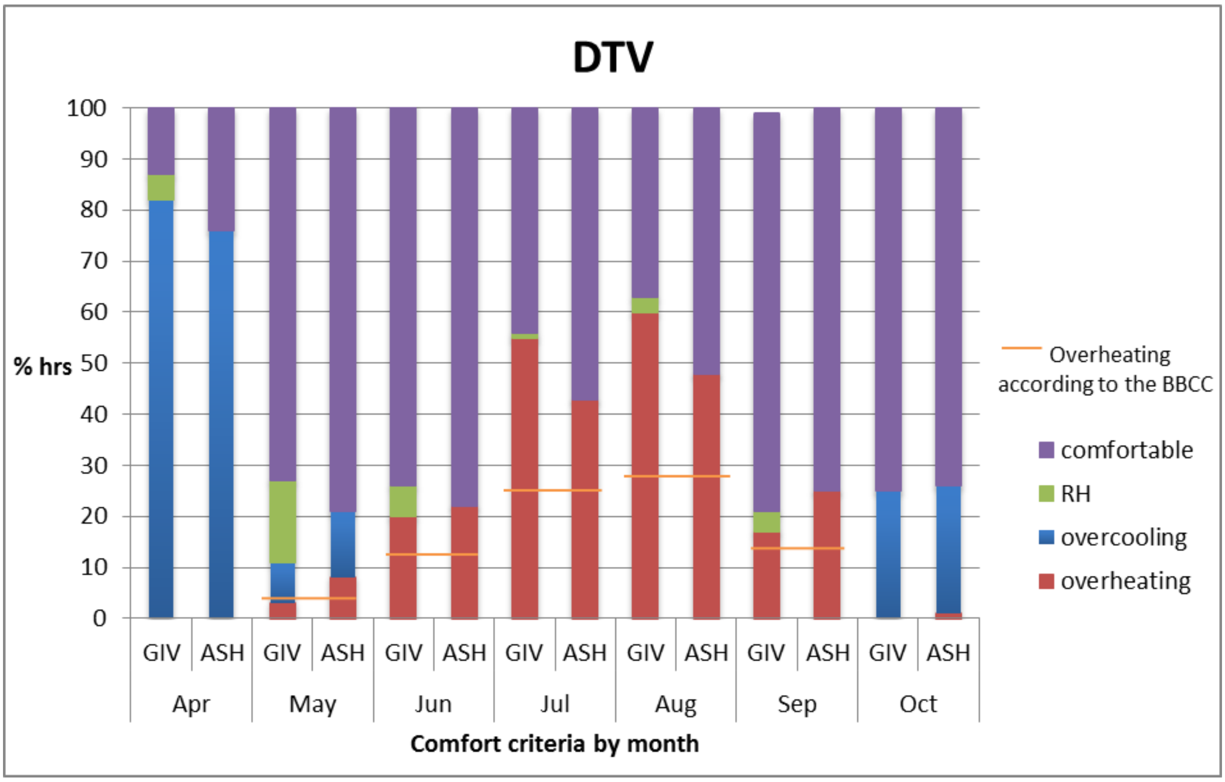


Figure 5.43: AH, DTV modelling potential in the hot dry region based on Givoni's and ASHRAE comfort criteria, as compared to the BBCC predictions, hot dry climate.

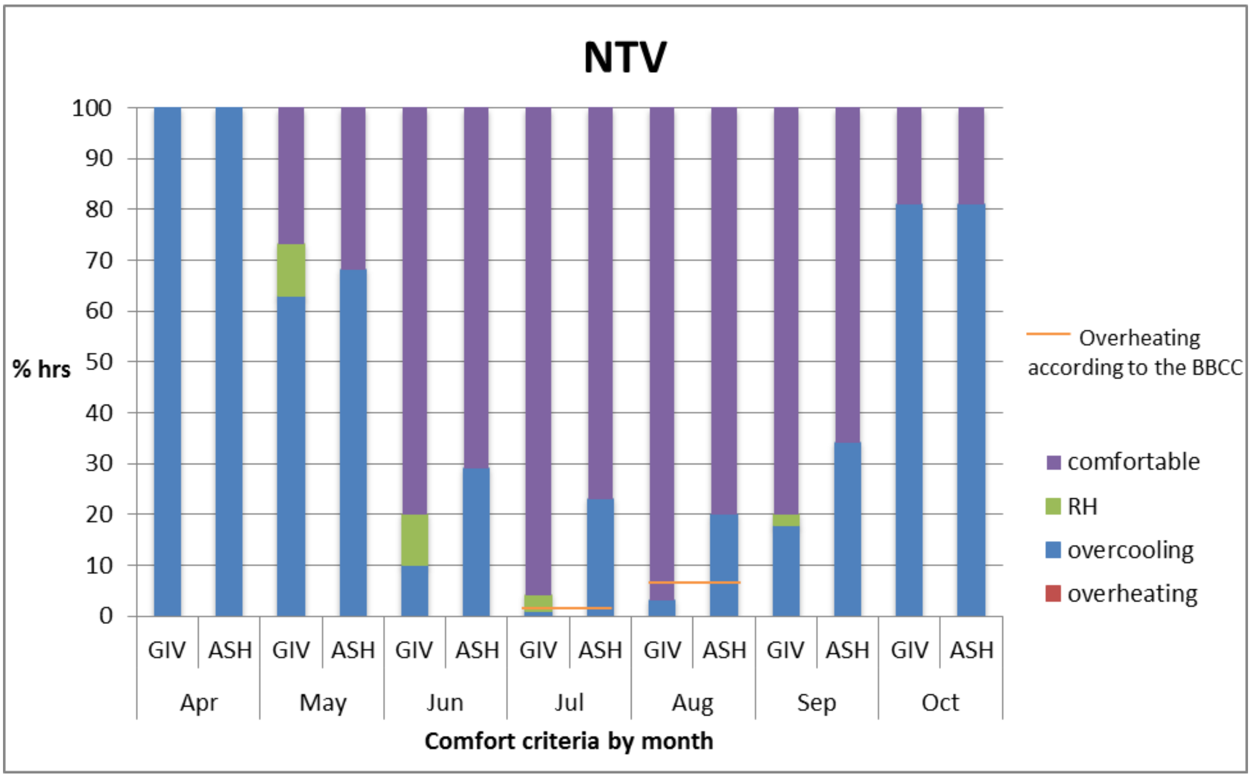


Figure 5.44: AH, NTV modelling potential in the hot dry region based on Givoni's and ASHRAE comfort criteria, as compared to the BBCC prediction, hot dry climate.

As demonstrated in Figure 5.43, the BBCC predictions for DTV agreed with the modelling results in April, May and October, a discrepancy of less than 10% is noted in May and September; however, the modelling predicted about 20% more overheating than the BBCC in the hottest months.

As for NTV, the modelled building did not overheat at all throughout the cooling season; on the contrary, the percentages of uncomfortable hours were due to overcooling of the building. On the other hand, the BBCC predicted minimal overheating in the hottest months.

The second exemplar (Casa Batroun) was also modelled using the Damascus weather file. Figures 5.45 to 5.48 show the percentages of uncomfortable hours as compared to the BBCC overheating hours for both BM and BT. Similar discrepancies to the previous house were observed in the DTV scenario. NTV was again found to sustain comfort even in the hottest months; however, the 1st floor overheated for about slightly less than 10% of the time, using ASHRAE zone.

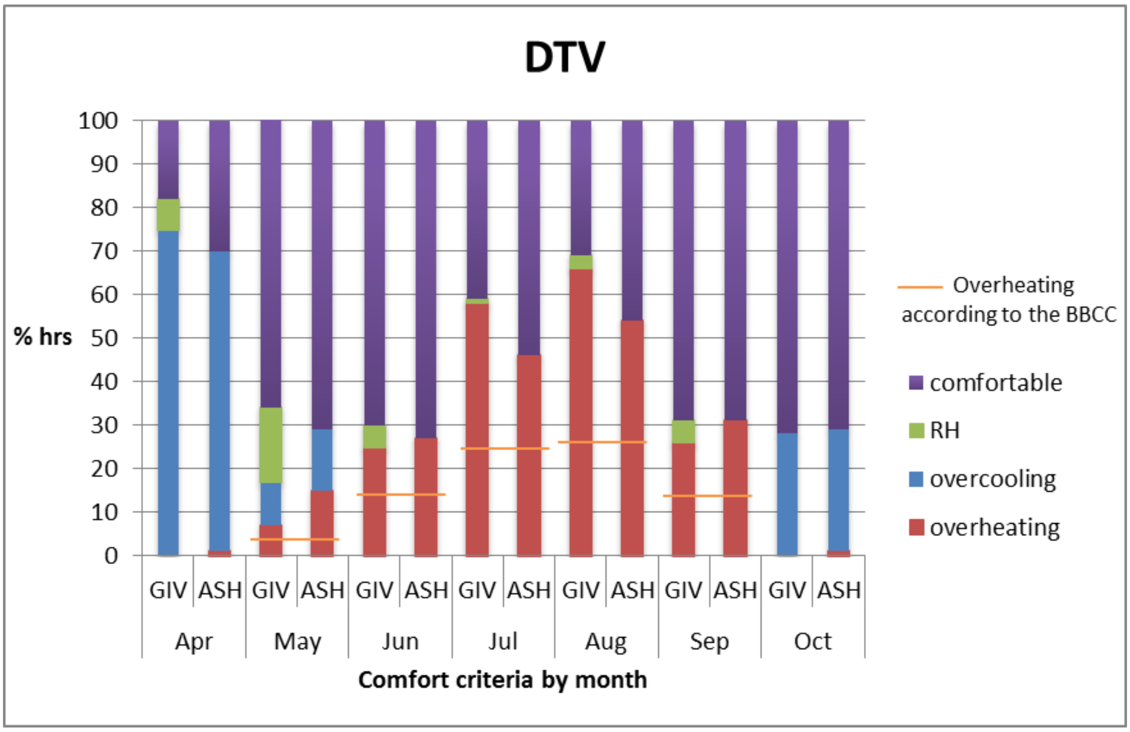


Figure 5.45: BM DTV modelling potential based on Givoni's and ASHRAE comfort criteria, as compared to the BBCC prediction, hot dry climate.

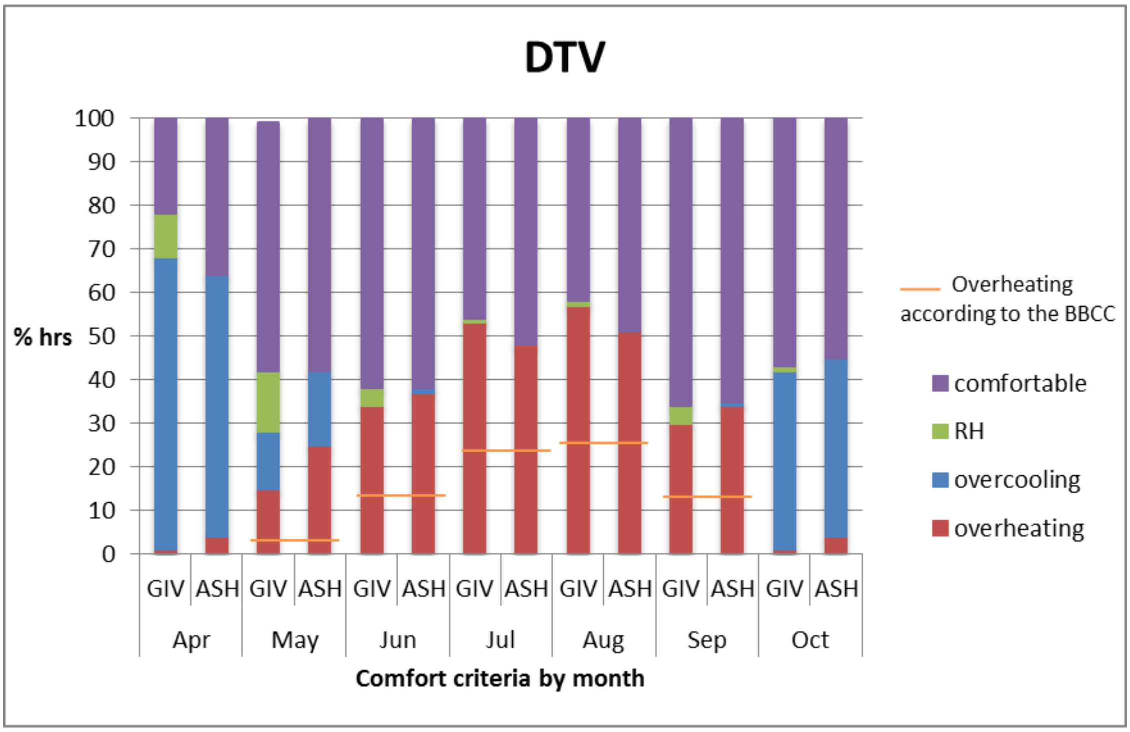


Figure 5.46: BT DTV modelling potential based on Givoni's and ASHRAE comfort criteria, as compared to the BBCC prediction, hot dry climate.

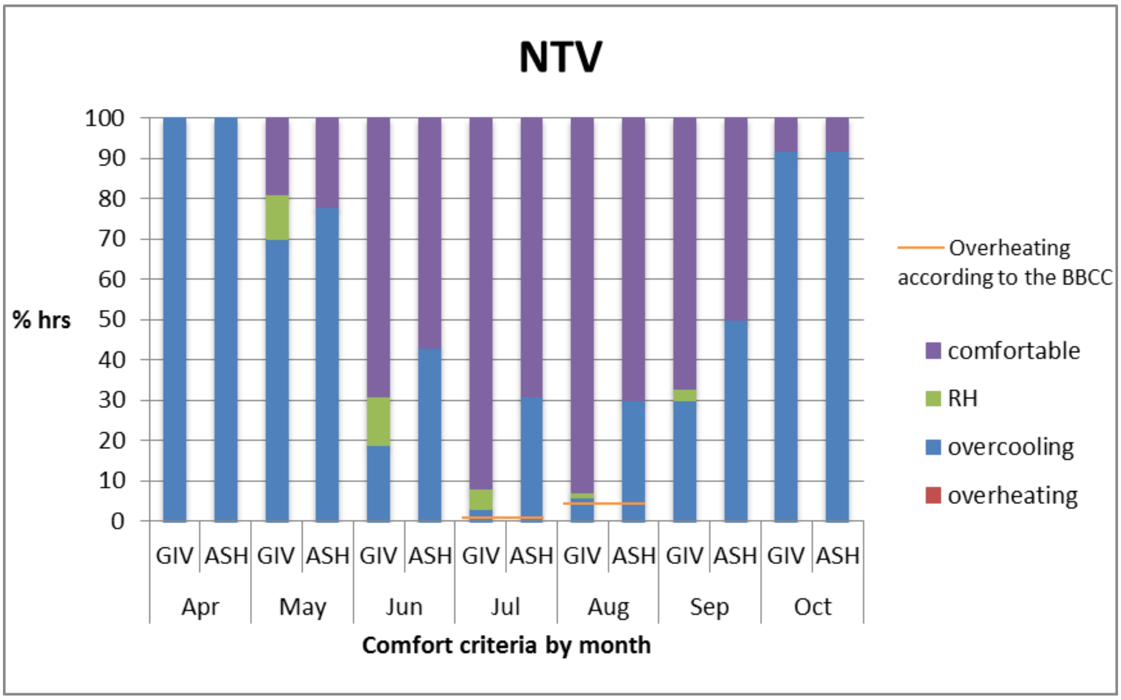


Figure 5.47: BM, NTV modelling potential based on Givoni's and ASHRAE comfort criteria, as compared to the BBCC prediction, hot dry climate.

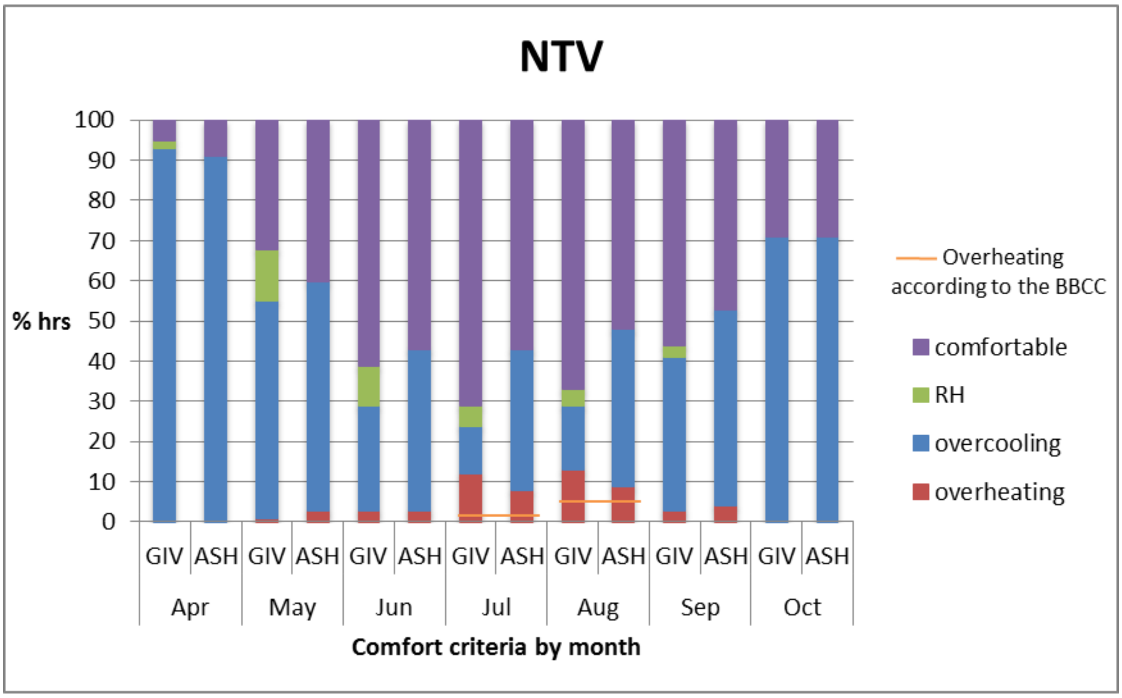


Figure 5.48: BT, NTV modelling potential based on Givoni's and ASHRAE comfort criteria, as compared to the BBCC prediction, hot dry climate.

5.7 Further analysis

Plotting hourly data on the psychometric charts for the selected climates illustrated the potential of DTV and NTV strategies in each climatic zone. A varying degree of discrepancy was noted between the BBCC predictions of overheating established in Chapter 3 (based on external weather data), and the resultant internal conditions established by the modelling of AH, BM and BT in the three studied climates. These discrepancies are summarised in Table 5.13.

Table 5.13: percentage of overheating hours discrepancy by which modelled buildings exceeded BBCC predictions as a function of climate, building type and comfort criteria.

			Climate		
Strategy	Building	Comfort Criteria	Warm-Humid	Hot-Dry	Very Hot-Dry
DTV	Heavy weight (AH & BM)	GIV	9%	7.4%	40%
		ASH	2.5%	6.4%	36%
	Light weight (BT)	GIV	12.4%	10.7%	N/A
		ASH	7.7%	12.4%	N/A
NTV	Heavy weight (AH & BM)	GIV	-7%	-2%	42%
		ASH	-9%	-2%	22%
	Light weight (BT)	GIV	2%	3%	N/A
		ASH	-1%	2%	N/A

It is apparent that the BBCCs significantly failed to predict the extent of overheating where cooling strategies were employed by both day time and night time ventilation in the very hot-dry region. Up to 36% and 22% more hours of overheating occurred for DTV and NTV respectively, using ASHRAE criteria. On the other hand, the modelling and the BBCC predictions almost agreed for NTV in the hot dry region. This demonstrates that the BBCC did not offer consistent predictions across all studied climates and that they were more accurate in predicting overheating in climates similar to those they were developed in. Given that the discrepancy was not the same across all studied climates; a climate-specific guidance was shown to be required rather than a generalised approach similar to the BBCC. The BBCC relies on boundaries of external maximum weather conditions above which comfort cannot be achieved by a certain strategy. However, it seems that the NTV potential, for example, was more sensitive to night-time minimum temperature and the diurnal range than it was to daytime maximum temperature. This could explain why the BBCC predictions agreed with modelling in the hot dry region, where the diurnal range is about 20K and night time minimum temperatures could drop to well below 22°C. While on the other hand, significantly failed to predict the number of overheating hours in the very hot dry region, where summer night time temperatures rarely drop below 26°C.

In order to summarize the potential of DTV and NTV and suggest suitable guidance for the main climatic zones in the Eastern Mediterranean, the following table was produced showing for what percentage of the time overheating is expected with DTV and NTV and when either or both strategies are recommended.

Table 5.14: The percentage of overheating hours expected for DTV and NTV strategies, blue means the strategy is recommended, red that it isn't.

Climate	Strategy	Apr	May	Jun	Jul	Aug	Sep	Oct
Hot dry	Day vent	0%	<10%	20-30%	40-50%	40-50%	20-30%	0%
	Night vent	N/A[1]	N/A	0%	0%	0%	0%	N/A
	Other cooling strategies required?	No	No	No	No	No	No	No
Very hot dry	Day vent	10-15%	30-40%	>50%	>50%	>50%	>50%	>50%
	Night vent	0%	<10%	30-40%	>50%	>50%	40-50%	<10%
	Other cooling strategies required?	No	No	Yes	Yes	Yes	Yes	No
Hot humid	Day vent	0%	0%	<10%	30-40%	50%	<10%	0%
	Night vent	N/A	N/A	<10%	<10%	<10%	N/A	N/A
	Other cooling strategies required?	No	No	De-humidification	De-humidification	De-humidification	No	No

[1] N/A not applicable: natural ventilation results in over cooling,

5.8 Uncertainty and sensitivity analysis

Several assumptions were made where information was missing, and many uncertainties existed pertaining to the building construction (as explained in 5.4.1.3). Additionally, assumptions made regarding occupancy patterns and uncertainties in weather files are common contributors to mis-matches between the simulated output and the monitored data. Uncertainty analysis may be undertaken to appraise the impact of the assumptions and simplifications made in any modelling studies due to lack of information in input data (Rodrigues et al., 2013). Sensitivity analysis may also be used to determine the relationship between assumptions about a particular input parameter and uncertainty in the resultant output (Helton et al., 2005). This section will first summarise the different approaches for conducting a sensitivity and uncertainty analysis. Then it will explain the approach chosen in this study followed by the results.

5.8.1 Overview on sensitivity and uncertainty analysis

There are several methods for conducting a sensitivity analysis. Screening methods identify the most important parameters out of large number of parameters and are used in complex situations such as environmental building design. Local sensitivity analysis determines the effect of one parameter at a time on the model output. Global sensitivity analysis is the most complex and can assess the interaction between parameters and their influence on the output (Heiselberg et al., 2009; Spitz et al., 2012; Encinas & De Herde, 2013). For global sensitivity analysis several sampling methods exist to generate an input vector/matrix such as the Monte Carlo method, random sampling, and the Latin hypercube sampling method (Heiselberg et al., 2009; Hopfe & Hensen, 2011; Spitz et al., 2012).

A review of environmental modelling input data showed that up to 130 input parameters could be affected by uncertainties (Rodrigues et al., (2013). However, they proposed that these parameters be separated according to their magnitude, into micro-parameters, such as the conductivity of a material in a composite wall, and macro-parameters such as the infiltration rate. In their study they concluded that uncertainties in weather data and occupancy were the most dominant factors that affected energy consumption, however when these two parameters were fixed and only 19 macro-parameters were studied, a better insight into the impact of the other parameters on energy consumption was possible. Breesch and Janssens (2004) conducted a sensitivity analysis and ranked the 14 most influential parameters on the uncertainty of thermal comfort in a night ventilated office room, concluding that the most influential parameters were internal heat gains and local outdoor temperature. Their conclusion demonstrates that Rodrigues et al., (2013) proposal to exclude dominant factors such as weather and occupancy from the uncertainty and sensitivity analysis is a plausible approach, especially given that designers have no control over such parameters.

After selecting the parameters to be analysed, the test ranges of each parameter and their mean value, standard deviation, and distribution should be defined. Uncertainties in input parameters are defined using probability distributions that could be discrete, uniform, triangular, log-normal or normal probability distributions, depending on each parameter. The most common distributions in sustainable building design are uniform, log-normal and normal distributions (Heiselberg et al., 2009). However, the results of sensitivity analysis depend to a greater extent on the selected ranges rather than the assigned probability distribution (Heiselberg et al., 2009). The ranges vary either side of a selected base input value where the values at each end of the range represent a possible extreme value for the selected parameter. Hopfe and Hensen (2011) specified the ranges of physical uncertainties according to Building Regulations in the Netherlands. Others might have based their selected ranges on common practice or experience. Tables 5.15 and 5.16 summarise ranges and intervals or mean and standard deviations (SD) for relevant micro and macro-parameters found in the literature.

Table 5.15: Mean, standard deviations and ranges for materials' thermal properties found in literature

Micro-parameter	Thermal Conductivity		Density		Specific heat capacity		Reference
	mean	SD	mean	SD	mean	SD	
Concrete block	1.41	0.1269	1900	28.5	1000	106	Hopfe & Hensen, 2011
Cast concrete	1.13	0.1017	2000	30	1000	106	Hopfe & Hensen, 2011
	1.54	0.3	1168	100	1050	100	Rodrigues et al, 2013
Cement screed	0.9	0.36	1452	382	910	152	Macdonald & Strachan, 2001
Mineral fibre	0.042	0.003	30	9	840	55	Rodrigues et al, 2013

Table 5.16: Mean, standard deviations and ranges for input parameters found in literature

Macro-parameter	Range	Interval	Mean	SD	Reference
Heat transfer coefficient of walls & roofs (W/m²K)	0.5 - 3.5	0.5			Yu et al; 2013
				±5% *	MacDonald, 2002
Infiltration rates (ach)	-		0.5	0.005	Rodrigues et al, 2013
			0.5	0.17	Hopfe & Hensen, 2011
	0.25 - 2	0.45			Jain et al; 2014
	0 - 0.3	0.1			Heiselberg et al., 2009
			0.115	±10%	Spitz et al., 2012
				±100%	Macdonald & Strachan, 2001

*Standard deviation in U-values due to measurement errors

A simple method was suggested by Heiselberg et al., (2009) to determine the design parameter sensitivity, it is given in equation (5.1). Yu et al., (2013) used Chow & Chan (1995) equation (5.2). Other studies have used regression analysis to determine sensitivity.

$$SI = \frac{E_{max} - E_{min}}{E_{max}} 100\% \qquad (5.1)$$

Where SI is the sensitivity index,

E_{max} and E_{min} represent the maximum and minimum output values, resulting from varying the design parameter over its entire range.

$$SI = \frac{(\frac{\Delta L}{L_n})}{(\frac{\Delta P_i}{P_{i,n}})} \quad (5.2)$$

Where ΔP_i is the variation of input parameter

$\Delta P_i = P_i - P_{i,n}$; P_i is the value of input parameter i

$P_{i,n}$ is the base value of each input parameter i

ΔL is the output variation for the change of input parameter

$\Delta L_i = L_i - L_n$; L_n is the output value of the base case

L_i is the output when the value of input parameter is P_i

5.8.2 Methodology chosen in this study

It was necessary here to distinguish between two different types of uncertainties in input data in the Aqaba house and Casa Batroun. The first were the uncertainties in material characteristics (aleatory uncertainties). The materials used and their densities, specific heat capacity or conductivity were known but considered as uncertain parameters. This would affect the overall U-values and thermal capacity of construction elements. Bad workmanship and uneven thicknesses of plaster or wool insulation materials are other common factors that affect the overall U-value. These uncertainties will also affect other derived parameters of construction elements such as the admittance Y-value. The second type of uncertainties was those due to lack of knowledge (epistemic uncertainties). For instance, the airtightness of both houses was not measured and the discharge coefficient of windows was unknown, in addition to uncertainties in the weather file and occupancy profiles.

Only uncertainty analysis due to assumptions made regarding the infiltration rate and the window discharge coefficients were conducted. Uncertainties in weather and occupancy were excluded based on Rodrigues et al., (2013) argument explained in the previous paragraph. Addressing uncertainties in material specifications was excluded because the impact of different constructions (with different U-values and thermal mass) is the subject of the parametric analysis carried out in chapter 6.

In order to assess the impact of uncertainties of the selected macro-parameters on comfort conditions in the house when naturally ventilated, single parameter analysis (one parameter at a time analysis) was conducted. The upper and lower limit of a selected range was evaluated for each selected macro-parameter while all other parameters were fixed. For windows with Venetian shutters, discharge coefficient ranged between 0.1 and 0.3 (as shown in section 5.4.1.3), 0.4 was taken as an upper limit. Figure 5.49 shows the range of infiltration rates of newly built constructions (ASHRAE fundamentals 2005).

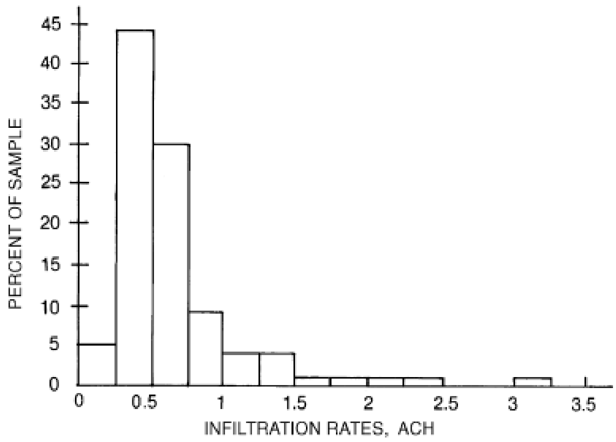


Figure 5.49: Infiltration rate in new built, (ASHRAE Fundamentals, 2005)

Table 5.17: Selected ranges for the macro-parameters studied

Macro-parameter	Base case	Upper limit	Lower limit
Infiltration rates (ach)	0.5	3.5	0.02
Windows discharge coefficient	0.25	0.4	0.1

5.8.3 Results

The results were evaluated in terms of the 'overheating hours', i.e. the percentage of time above the upper comfort limit of the ASHRAE comfort zone outlined in Chapter 3. Tables 5.18 and 5.19 show the results of uncertainty analysis for each of the selected parameters with the base case. The discharge coefficient of the windows with Venetian shutters had no noticeable effect on the overheating hours above the comfort temperature when the building was ventilated during the day, as indicated by the resultant horizontal line graphs. However, when the building was ventilated at night (see Figure 5.50), the window discharge coefficients had a slightly greater impact especially during the hotter months. It should be noted here that in both cases (DTV and NTV,) the discharge coefficient did have an effect on the ventilation rate, but for DTV the corresponding variation had little influence on the overheating hours observed, this is further discussed in Chapter 7.

Table 5.18: Percentage of overheating hours for the discharge coefficient range

Discharge coefficient		Apr	May	Jun	Jul	Aug	Sep	Oct
Day Vent	Min value (0.1)	26.5	61.4	99.6	100	100	99.3	65
	Base case (0.25)	27.1	62.2	99.4	100	100	98	65
	Max value (0.4)	31.3	62.7	99.3	100	100	98	64.7
Night Vent	Min value (0.1)	0.6	19.5	77	90.3	92.3	68.9	21.2
	Base case (0.25)	0.8	19	76	89.6	91.2	66.9	19.4
	Max value (0.4)	0.9	19.3	75.2	88.9	90.3	65.4	18.1

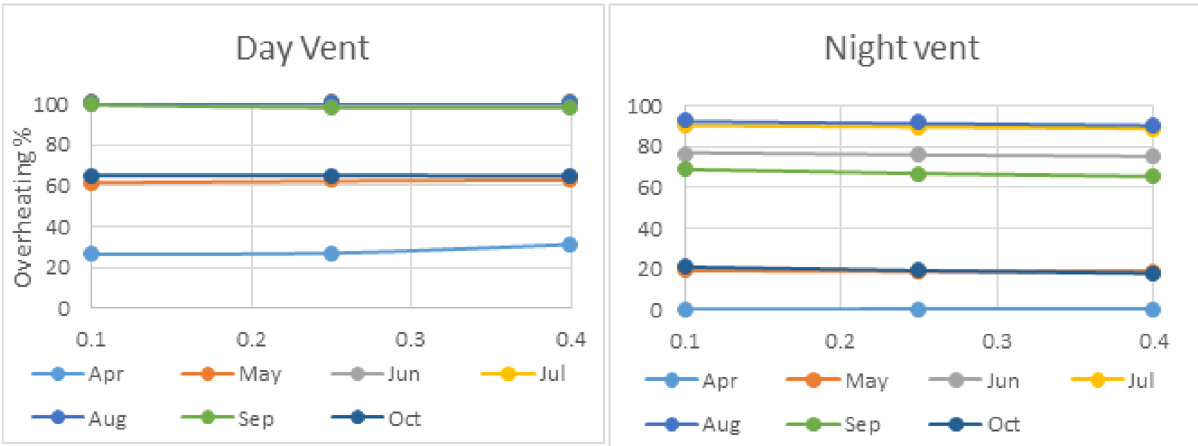


Figure 5.50: Overheating hours' sensitivity to discharge coefficients (0.1 to 0.4), day vent (left), night vent (right).

The infiltration rate had a greater impact during the cooler months of April, May and October, but almost no effect during the hottest months from July to September in daytime ventilation and night-time ventilation scenarios (Figure 5.51).

For the cooler months, (where the infiltration rate impinges on the percentage of time above the comfort temperature,) an increased infiltration was shown to have a detrimental effect for the night time ventilation case and beneficial in the daytime ventilation case. This is indicated simply by the overall negative gradient of the DTV plot and positive gradient of the NTV plot, Figure 5.51.

Table 5.19: Percentage of overheating hours for the infiltration rate range

Infiltration rate (ach)		Apr	May	Jun	Jul	Aug	Sep	Oct
Day Vent	Min value (0.02)	27.6	66.3	99.7	100	100	98.4	67.1
	Base case (0.5)	27.1	62.2	99.4	100	100	98	65
	Max value (3.5)	23.1	51.5	98.4	100	100	93.7	51.7
Night Vent	Min value (0.02)	0.6	17	74.3	89.1	90.9	65	14.9
	Base case (0.5)	0.8	19	76	89.6	91.2	66.9	19.4
	Max value (3.5)	9.9	28.5	79	90.5	91.9	70.6	28.9

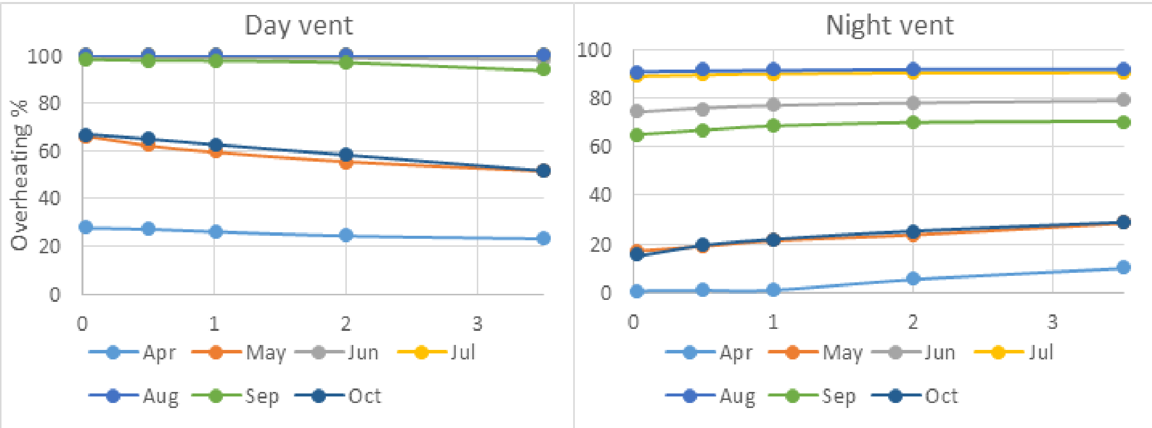


Figure 5.51: Overheating hours' sensitivity to infiltration rate (0.02 – 3.5ach) day vent (left), night vent (right).

It could be concluded that a naturally ventilated building is more sensitive to infiltration rate than window discharge coefficients. Both variables affect the overall hourly air change rate in the building. However, it seems that the discharge coefficient of windows had very little impact on the resultant flow rate through the windows. The sensitivity to infiltration rate was due to higher rates allowing ventilation when the windows were meant to be closed, resulting in ventilation heating gains during the day in the case of NTV, and night cooling in the case of DTV. Nonetheless, the overall number of overheating hours was not very sensitive to either parameter, as the difference in the percentage of overheating hours for the maximum and minimum values of the selected ranges was less than 5%.

5.9 Summary

Full building thermal performance analysis using dynamic modelling software IES VE was carried out using Aqaba city as representative of the very hot-dry climatic zone, Beirut city as a representative of hot-humid zone and Damascus city as representative of a hot-dry zone. Two existing best-practice houses configurations were used in the analysis. The results of the modelling demonstrated the following:

- In a very hot and dry zone, even very thermally heavy, well insulated and well shaded buildings could not passively provide comfortable internal conditions when naturally cross ventilated employing either day time or night time ventilation.
- In a hot humid zone, building designs that encourage cross ventilation are a sufficient solution that can limit the number of overheating hours. Heavyweight buildings are more desirable, however, high humidity levels remain an issue and air velocities within rooms in urban environments may not always be high enough and fan assistance may be required.
- In a hot dry zone, night time ventilation was sufficient for maintaining comfortable indoor environments and therefore it is a highly recommended strategy.
- Uncertainty analysis for infiltration rates and window discharge coefficients was conducted. The sensitivity of indoor temperature to variations in these parameters was assessed. They were found to have minimal impact on the overall overheating hours for the range of infiltration rate or the window discharge coefficients expected in the studied buildings, meaning that the above conclusions remained appropriate.

Figure 5.52 sums up the findings of this chapter on the potential of nighttime ventilation in all three climates studied.

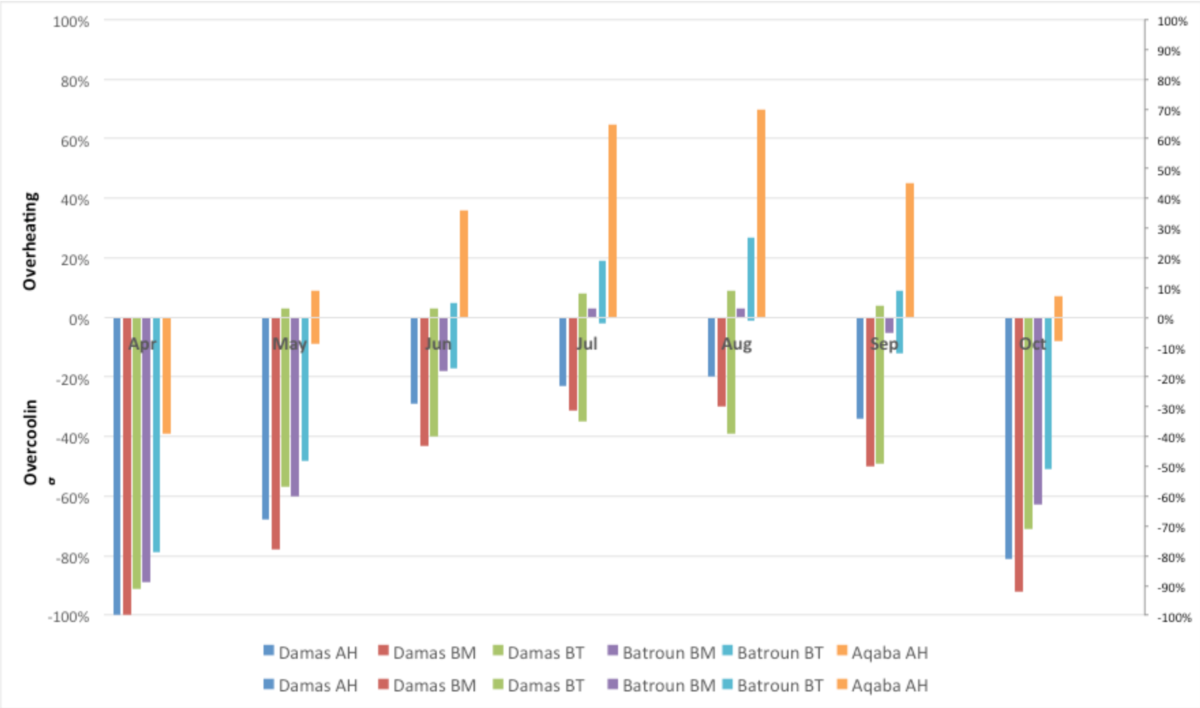


Figure 5.52: NTV percentage of time of uncomfortable hours according to ASHRAE adaptive comfort standards

Chapter 6: Parametric Analysis of Design Options

The study of best practice buildings in the three main climatic zones of the EM showed that additional cooling (whether passive or active) was required in the very hot dry regions. In other words, regardless of the construction type, natural ventilation alone could not achieve thermal comfort in this region. The house studied in the hot humid zone had two types of constructions, timber and masonry. The results showed that the masonry construction had greater potential to exploit NTV, however, the very high moisture content in the air required dehumidification. The only region in which NTV and DTV could be best exploited without the need for additional strategies was the hot dry zone. This Chapter aims to evaluate the effectiveness of different typical and best practice constructions and evaluate their natural ventilation potential.

6.1 Selecting construction types

Building envelopes are the link between the external and internal environment and play a vital role in the resultant internal temperatures. It has been established that well insulated buildings with lower U-values have lower energy consumption. In naturally ventilated buildings, the thermal mass of the construction, its ability to store coolth and delay the occurrence/severity of peak temperatures, is a main contributor to maintaining indoor comfort conditions (Artmann et al., 2008). This thermal mass effect may be evaluated in terms of an elemental admittance, surface factor, decrement factor and the associated time lag.

The admittance Y-value (W/m^{2}K) is mostly affected by the inner part of the wall so as the wall thickness increases the admittance value becomes constant. For very thin walls or those with low thermal conductivity the U-value and the Y-value are the same. Although the Y-value has the same units as the U-value, higher values are desirable for the Y-value. The admittance is defined as “a measure of the ease by which energy will pass through the internal surface of the element to, or from, the room per degree of temperature difference between the surface at a particular time and the 'room' average temperature" (Dwyer, 2012).

The decrement factor represents the relationship between indoor and outdoor temperature swing. The surface factor is the ratio of short wave radiant heat flow readmitted to the space to the heat flow incident on the wall. The thermal capacity (Cm), or the effective thermal mass of a wall, is the product of density, thickness and heat capacity. Thermal capacity is measured, starting on the internal face, moving outwards until either (i) a point 100 mm from the internal face is reached; or (ii) the Mid-point of the wall is reached; or (iii) Insulation layer is reached.

To assess the impact of different wall assemblies on internal temperature, several scenarios of medium to heavy mass walls were modelled under different ventilation rates. Evaluating light weight constructions were excluded from this study as the common practice in the EM region is to build with masonry, brick or concrete blocks, all fall into the heavy weight construction category. Additionally, it was well established that NTV was most effective with higher mass. The aim of this study was therefore only to compare current practice constructions to best case constructions such as those used in the Aqaba house, and establish whether the expected improvement in comfort for naturally ventilated buildings were worth the extra investment associated with enhanced envelope constructions.

The Aqaba house had three main types of constructions (outlined in section 5.4.1.1) depending on the wall orientation. These were; an insulated cavity wall, a filled cavity wall, and an insulated and filled cavity wall (walls 1, 2 and 3). It wasn't possible in the modelling of the base case in Chapter 5 to note the difference in these walls performance. To compare these constructions, AH was re-modelled using one construction at a time. Common practice in the EM region is to build external walls with concrete blocks (Census, 2004) as either one layer of blocks or as uninsulated cavity walls. Limestone is commonly used as an external cladding, in several cities it is a mandatory requirement (Aleppo building regulations, 2010). Based on this the typical practice wall assemblies modelled in this chapter were; an uninsulated cavity wall and an uninsulated single block construction using medium weight concrete blocks. In addition, an externally insulated single block construction was also modelled as a potential enhancement to typical practice. Figure 6.1 illustrates these details, and Tables 6.1 and 6.2 describe their thermal properties.

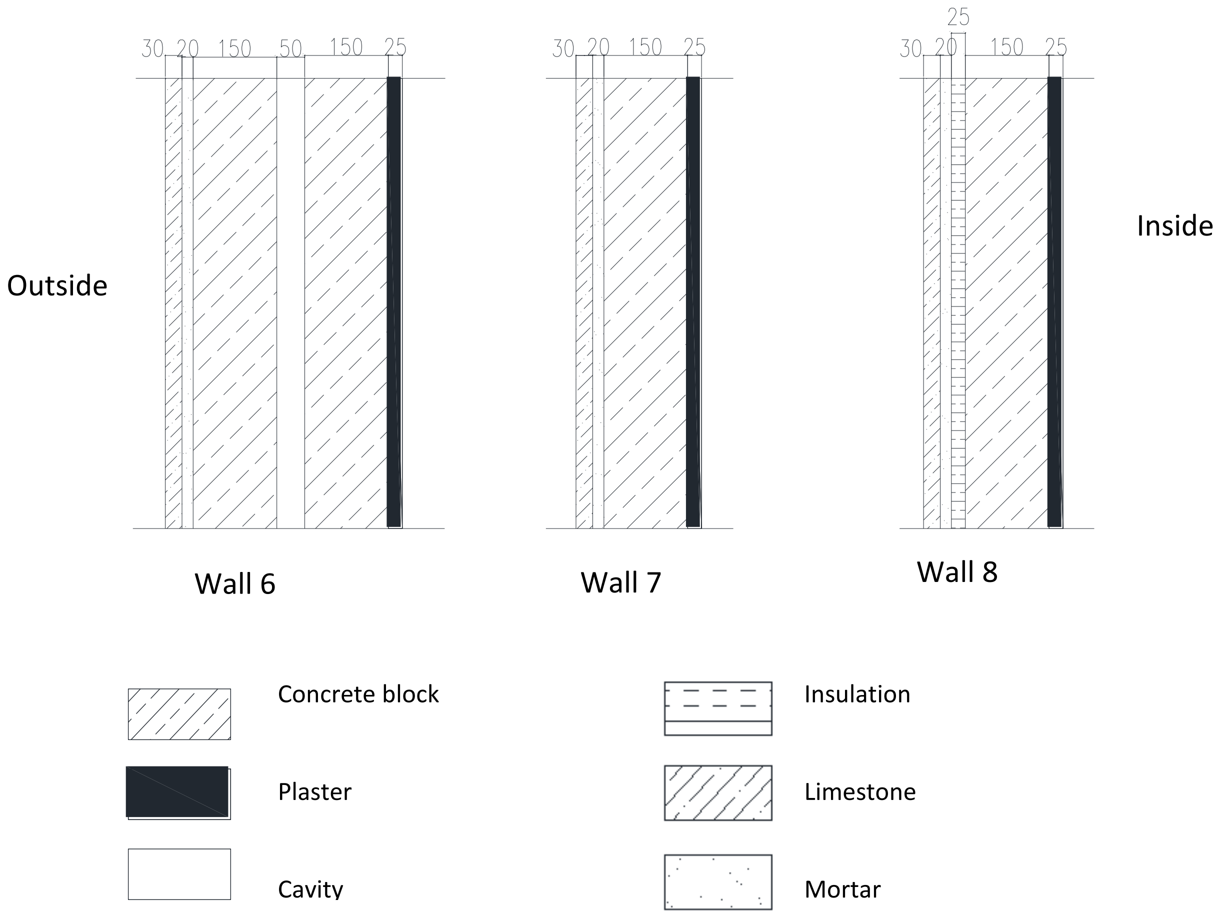


Figure 6.1: Typical wall constructions (dimensions in mm)

Table 6.1: Typical practice wall assemblies

Wall ID	**Description**	**Thermal properties**				
		Thermal capacity KJ/m^2K	Admittance W/m^2K	Decrement factor	Surface factor	U-value W/m^2K
Wall 6	Uninsulated cavity wall	137.5	4.31	0.127	0.58	0.96
Wall 7	Single block layer	137.5	4.25	0.471	0.59	1.77
Wall 8	Externally insulated single block layer	137.5	4.36	0.261	0.57	0.71

From Chapter 5, Table 5.5

		Thermal capacity Cm KJ/m^{2}K	Admittance W/m^{2}K	Decrement factor	Surface factor	U-value W/m^{2}K
Wall 1	Insulated cavity	67.75	3.6	0.303	0.71	0.36
Wall 2	Insulated & filled cavity	67.75	3.24	0.068	0.73	0.35
Wall 3	Filled cavity	88	3.7	0.139	0.65	0.93

Table 6.2: Thermal properties of materials used in typical practice (IES database)

Materials	**Thermal properties**			
	Thickness	Conductivity	Density	Heat capacity
	mm	W/m.K	Kg/m^3	J/kgK
Limestone	30	1.5	2180	720
Cement mortar	20	0.72	1860	800
Concrete block	15	0.51	1400	1000
Insulation (polystyrene)	25	0.030	25	1380
plaster	25	0.57	1300	1000

6.2 Analysis of typical and best practice constructions

The Aqaba house base case was modelled again for each of the selected wall assemblies. Occupancy, internal gains and other assumptions remained the same as the base case. However, the ventilation rate specified in the thermal model starting from 1 ach up to 20 ach for NTV.

The results of NTV modelling of best and typical practice showed that little variation existed between all the wall constructions, for 1 ach the building overheated for 10 to 12% of the time in the hottest month of August. Above 10 ach no significant improvement could be delivered by NTV. Wall 8 (enhanced typical practice) was found to perform better than best practice walls used in the AH, Figure 6.2. AH had 45cm thick walls but the improvement to thermal comfort delivered by such an approach was insignificant if the building was to be naturally ventilated. The results of this analysis could be explained by the following; the selected typical constructions had normal medium-weight concrete blocks, while AH constructions had perlite or volcanic aggregate concrete blocks. These blocks had lower thermal conductivity and density than the selected medium weight block. The thermal capacity of the walls, their admittance and surface factors are related to the inner layer of the walls. The very inner layer of all walls was the same (plaster); the following layer was either, the medium weight concrete block, the perlite aggregate or the volcanic aggregate blocks. This resulted in the relatively similar performance of all wall assemblies. Wall 8 performed best because of its high thermal capacity compared to the other constructions, while its relatively lower U-value helped protect the building from gaining heat through the walls during the day when the windows were closed and thus maintaining the coolth stored in the walls overnight.

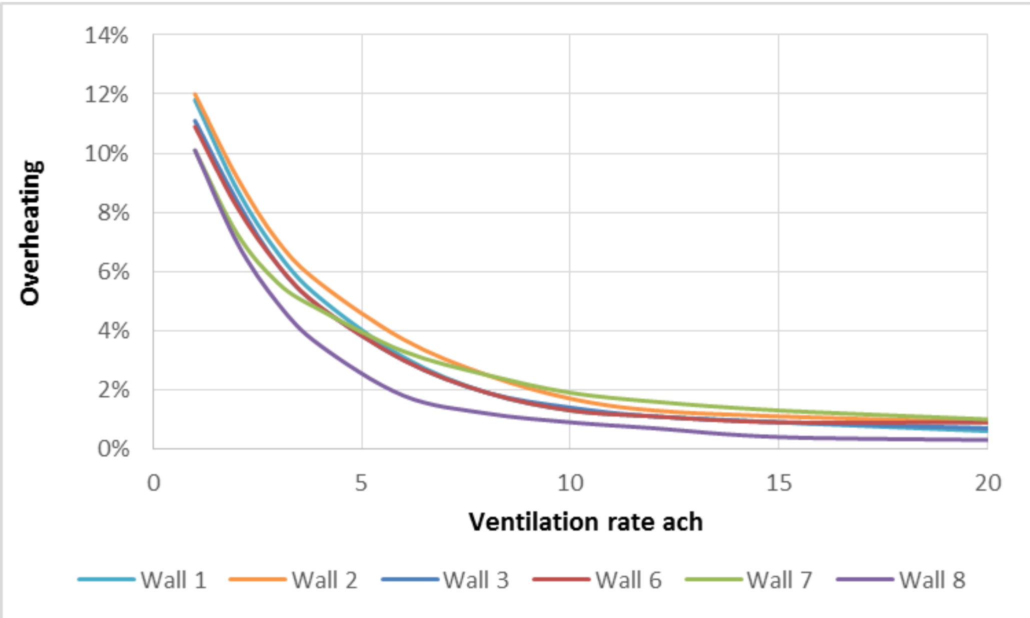


Figure 6.2: overheating with NTV in the hottest month for different wall constructions at different ventilation rates.

Another benefit in wall 8 construction is that 6 ach at night were sufficient to reduce the overheating hours to below 2%, while the remaining wall constructions required between 8 to 10 ach to achieve the same.

AH was well shaded with Venetian shutters and overhangs, which means that very little solar gain was observed in the previous study and that detailed above. If the Venetian shutters were to be opened during the day, to allow views or for any other reasons, the solar gains would be expected to increase. This is a reasonable occurrence in practice and would affect the performance of all the studied constructions. The thermal mass effect might be more pronounced with higher solar gains, therefore, the above analysis was repeated but without the Venetian shutters.

6.3 Analysis of typical and best practice construction without shading (Venetian shutters)

The Venetian shutters were removed and the parametric analysis in 6.2 was repeated. Overhangs and window reveal recess, remained the same as they are part of the structure, while the Venetian shutters are a user-dependant variable. All other parameters in the base case remained the same.

Removing the Venetian shutters increased the daily solar gains in South-Eastern rooms in August from about 42 Wh/m^2 of floor area (2.8 W/m^2) to 216 Wh/m^2 (14.4 W/m^2), and in North-Western rooms from 29 Wh/m^2 (1.9 W/m^2) to 132 Wh/m^2 (8.8 W/m^2). This has doubled the total overheating hours in August for 1 ach ventilation rate; however the difference diminishes as the ventilation rate increases. This highlights how night ventilation for the hot-arid region is a very useful strategy, provided that rates higher than 6 ach could be achieved, as it is not very sensitive to construction type or solar gains above this air change rate; see Figure 6.4. Such a rate might not be achievable in practice especially in dense urban environments, and a fan-assisted night-time ventilation might be required.

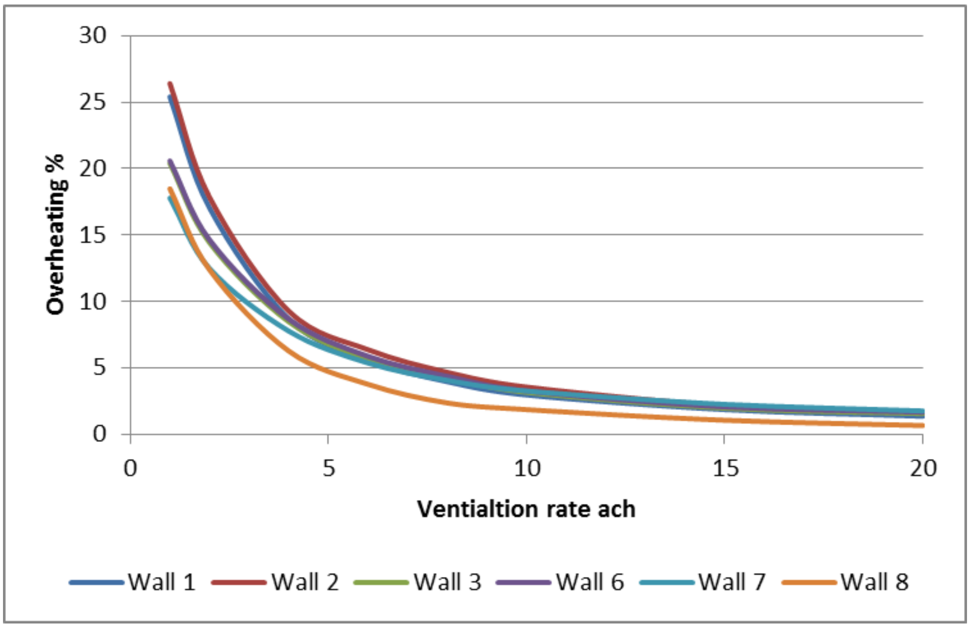


Figure 6.3: overheating with NTV in the hottest month for different wall constructions at different ventilation rates without Venetian shutters.

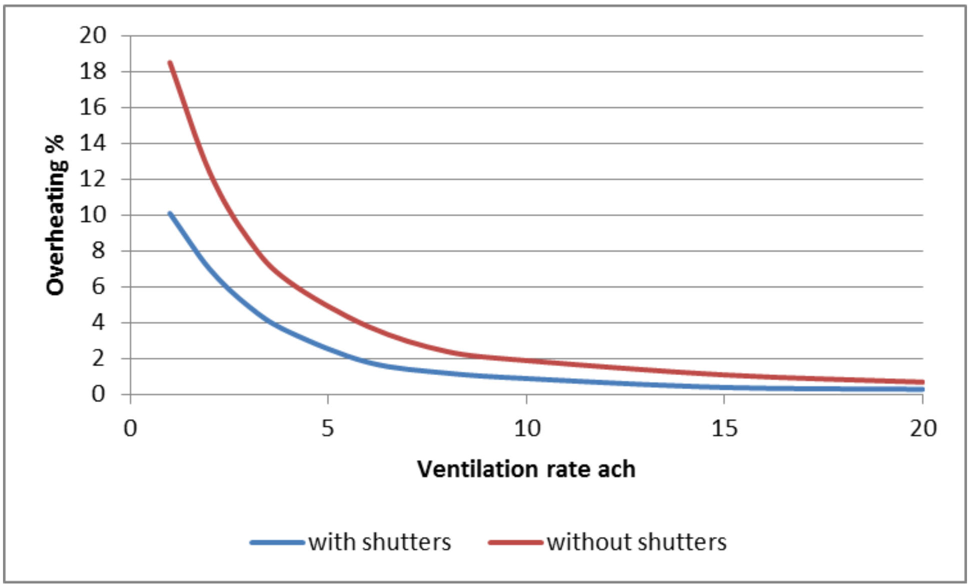


Figure 6.4: overheating with NTV in the hottest month for Wall 8 (insulated single block layer) at different ventilation rates with and without Venetian shutters.

6.4 Summary:

In the previous Chapter NTV was found to be capable of providing thermal comfort in the hot arid region even in the hottest summer months. Based on that typical wall constructions in the region were selected, and AH was modelled again for each of these constructions. The modelling was repeated again but without Venetian shutters to assess the effect of increased solar heat gains. It was found that insignificant differences existed between the performance of best practice constructions and typical constructions and so the additional costs of best practice wall constructions are not economically viable. Additionally, NTV could cope with solar heat gains up to 15 W/m^2. However, low ventilation rates limited the potential of NTV and air changes above 6 ach are recommended. Therefore, layout designs that encourage cross ventilation should be promoted.

Chapter 7: Monitoring of best practice buildings

During the summer of 2013, the selected buildings modelled in Chapter 5 were each monitored when naturally ventilated for 2 weeks. This was done in order to collect real data on the performance of both buildings with daytime ventilation DTV and nighttime ventilation NTV. A survey of recent literature (2005 onwards) by Zhai et al., (2011) demonstrated that the majority of research on natural ventilation is conducted by computer modelling. No more recent surveys are available. There is a lack of post-occupancy performance data from naturally ventilated buildings especially in hot climates where such strategies were applied. Most post-occupancy studies focus on the energy consumption of buildings rather than their passive performance, or were conducted as part of adaptive comfort surveys.

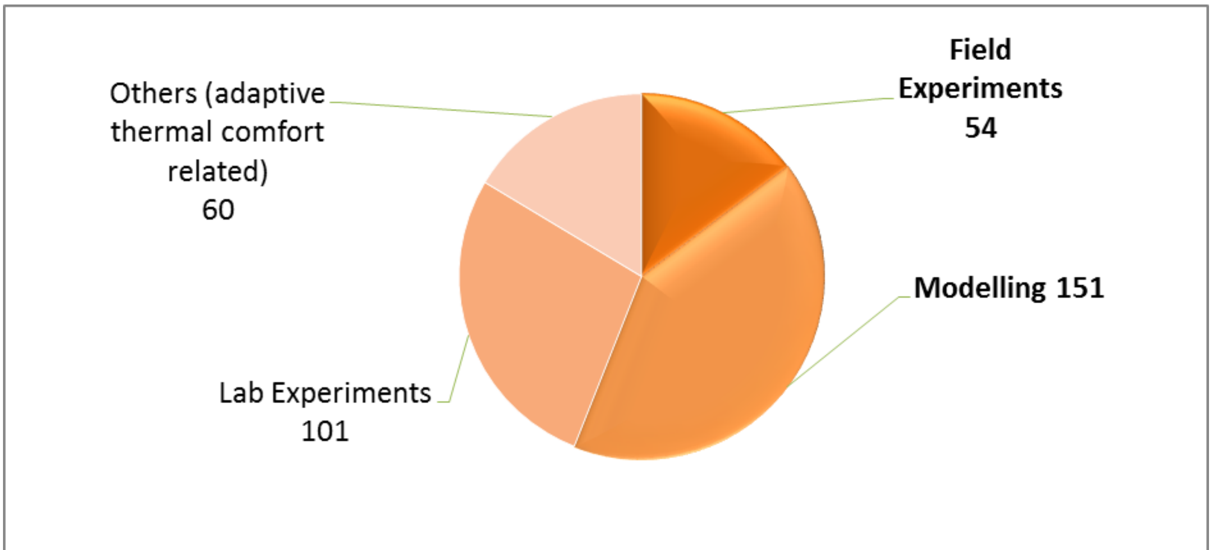


Figure 7.1: Publications on natural ventilation (adapted from Zhai et al., 2011)

7.1. Monitoring parameters

According to ASHRAE Standards 55 (ASHRAE, 2013), three variables were needed to determine comfort in naturally conditioned spaces, these were, indoor air temperature, indoor mean radiant temperature and outdoor air temperature. Nicol et al., (2012) outlined detailed information on the physical environmental variables that needed to be assessed when conducting a thermal comfort survey. Although, no comfort survey was conducted as both buildings weren't occupied during the monitoring period, the environmental variables required to establish the thermal performance of the buildings were the same. Ideally, internal room variables that should be monitored were air temperature, globe temperature, radiant temperature, operative temperature, air velocity, and relative humidity. Globe temperature mimics the response of the human body in its balance between radiant and convective heat exchange. Radiant room temperature is very complex and costly to measure so it is usually sufficient to obtain the mean radiant temperature calculated from air temperature, globe temperature and air speed (Nicol et al., 2012). Operative temperature is used to express room temperature as in ASHRAE-55 standards. It's defined by Nicol et al., (2012) as "an index that combines the air temperature and the mean radiant temperature into a single value to express their combined effect." The operative temperature is also used in some software packages to describe 'room temperature' or 'dry resultant temperature'.

For air direction measurement, small, weighted, helium filled balloons can be used. To measure air velocity hot-wire anemometers are most appropriate for internal air movement, and rotating-vane anemometers for external wind speeds (Nicol et al., 2012).

In order to assess the outdoor microclimate the following parameters were required: i) the outside air temperature, ii) relative humidity, iii) wind speed and direction, and, iv) global solar radiation on the horizontal plane.

7.2 Monitoring devices and strategy

Room temperature can vary from place to place within one room therefore; in thermal comfort surveys, when the occupants' immediate thermal environment is of particular interest; measurements are recommended to be taken at a vertical height of 0.6m above the floor for a seated person or at the working surface level and not less than half a metre from any wall (Nicol et al., 2012). ASHRAE Standards 55 recommend that, in cases where occupancy distribution cannot be estimated, a measurement in the centre of the room to be taken and measurements 1m inward from the centre of each wall or the largest window.

The height above the floor for air temperature and average air speed should be measured at the 0.1m, 0.6m, and 1.1m respectively for seated occupants. Measurements for standing occupants should be made at heights of 0.1m, 1.1m, and 1.7m above floor level. However, if the objective is to establish the overall performance of a space then a measurement in the centre of the room is sufficient. If the area of interest was the performance of a particular strategy, then measurements at several points in the room were needed such as; the air temperature near the ceiling or close to the inlet (Nicol et al., 2012). Ideally more than one sensor should be used at the same location for accuracy.

For humidity measurements, one measurement in the centre of a room is sufficient as levels do not vary in the same way as air temperatures do (Nicol et al., 2012). It also varies little from room to room (with the exception of kitchens) unless a particular humidifying strategy is used.

The approach of this research is to evaluate internal comfort enhancement by natural ventilation. However, the monitored buildings were unoccupied during the monitoring period and no human response to the environment was recorded. Therefore air temperature measurements in the centre of the rooms were sufficient to establish any comfort enhancement delivered compared to outside conditions. For the purpose of this study all sensors were placed on tripods in the centre of the rooms and connected wirelessly to a data logger.

Two types of sensors were used to measure room temperature, ventilated combined temperature/relative humidity devices that measured air temperature and relative humidity, in addition to black painted temperature sensors to account for the radiant temperature and give the dry resultant temperature (operative temperature). For air velocity, cup anemometers were used instead of the recommended hot wire anemometers. This is due to the limited budget of the project and the relatively large scale of the buildings monitored, requiring at least 10 anemometers. Hot wire anemometer, which are capable of measuring very low air velocities (mm/s) are costly, fragile and require constant care as it is easily contaminated in field studies (Doraisway, 2012). While cup anemometer are not capable of measuring very low air velocities, however, the main purpose of measuring air velocity in the middle of the rooms was to assess whether high enough air speeds for cooling sensation could be achieved by natural cross ventilation.

A weather station was set up on the roof of the studied buildings; this included an ultrasonic anemometer to measure wind speed and direction, a combined temperature and humidity sensor and pyranometer for global solar radiation onto the horizontal. Table 7.1 summarises the variables measured and the number of sensors used, their accuracy and location.

The sample period of temperature, RH and global solar radiation measurement was one minute with averages recorded every 30 minutes because of the insignificance of variation in recorded measurements observed in less than 30 minutes intervals Air speed/velocity and direction were recorded for every minute.

Table 7.1: Summary of monitoring sensors and location

VARIABLE		Location		Caveats	Number of sensors	Sensor type	Sensor accuracy
		Recommended	Applied				
EXTERNAL VARIABLES (MET STATION)	**Relative humidity & Air temperature** Appendix F	• 2.5m above the ground • 2.5m away from any wall	• 1.2m above roof surface, 11m above ground	• Avoid pet intrusion • Avoid direct wind/draughts	2	Shielded outdoor humidity & temperature transmitter	T < ±0.3K RH < 3%
	Wind speed & direction Appendix B	• 10m above the ground, or • 2.5 m above the roof of the building	• 2.7m above the roof surface, about 14m above ground	• Minimise pest/bird interference	1	Ultrasonic anemometer	Speed < 2% Direction < ±3°
	Global Solar Radiation Appendix D	• 2.5m mast on the roof	• 2m mast on the roof (higher than all obstructions)	• Avoid local over-shadowing • Minimise pest/bird interference & soiling	1	Silicon pyranometer	< 10%
INTERNAL VARIABLES	**Combined air temperature & relative humidity** Appendix F	• 0.5m distance from any wall • 0.6m above the floor • Centre of the room	• 1.2m above the floor • Centre of the room	• Avoid direct solar radiation • Avoid draughts • Avoid heat sources (TVs and other appliances)	5	Ventilated indoor humidity & temperature transmitter	T < ±0.3K RH < 3%
	Operative temperature Appendix E	As above	As above	As above	5	Integrated temperature transmitter	< ±0.5 K
	Air velocity Appendix C	• Centre of the inlet • Centre of the room • Centre of the outlet	Centre of few inlet/outlet Centre of the room (for cross ventilation)	• Avoid tampering (spinning)	10	Cup anemometer	±0.22m/s

7.2.1 Al-Aqaba house (AREE)

The following table and figures illustrate the locations and numbers of the sensors for Al Aqaba house and the monitoring strategy.

Table 7.2: Monitoring schedule

Day	Strategy	Ventilation time
Tue 23-07-13	Day-time vent/shutters closed	7 am – 8 pm
Wed 24-07-13	Day-time vent/shutters closed	7 am – 8 pm
Thu 25-07-13	Day-time vent/shutters closed	7 am – 8 pm
Fri 26-07-13	Day-time vent/shutters closed	7 am – midnight
Sat 27-07-13	Night-time vent – Also day vented on the previous day	midnight – 7 am 10 pm - midnight
Sun 28-07-13	Night vent only/shutters closed	midnight – 7 am 10 pm - midnight
Mon 29-07-13	Night vent only/shutters closed	midnight – 7 am 10 pm - midnight
Tue 30-07-13	Night vent only/shutters closed	midnight – 7 am 10 pm - midnight
Wed 31-07-13	Night vent only/shutters closed	midnight – 7 am 10 pm - midnight

Figure 7.2: Plans, sensors' location

Figure 7.3: ultrasonic anemometer and temperature and RH sensor (right), pyranometer (left)

Figure 7.4: anemometer, temperature and humidity sensors mounted on tripods in the centre of the rooms

Figure 7.5: the data logger placed on the 1st floor terrace

7.2.2 Casa Batroun

The following table and figures illustrate the locations and numbers of the sensors for Casa Batroun and the monitoring strategy.

Table 7.3: Monitoring schedule

Day	Strategy	Ventilation time	Notes
Mon 02/09	Occupancy (mixed)	3 pm- midnight	
Tue 03/09	Day-time vent/ shutters closed	midnight-20:30	
Wed 04/09	Day-time vent/ shutters closed	07:30 – 20:00	2nd floor northern Window open at night (sensor 1)
Thu 05/09	Day-time vent/ shutters closed	08:00 – 20:00	
Fri 06/09	Day-time vent/ shutters closed	08:00 – 20:00	Oven on at 22:00 for 40 min
Sat 07/09	Day-time vent /shutters closed	08:00 – midnight	
Sun 08/09	Night-time vent/shutters close	Midnight -7am 21:00 – midnight	
Mon 09/09	Night-time vent/shutters close	Midnight -7am 20:00 – midnight	
Tue 10/09	Night-time vent/shutters close	Midnight -7am 21:00 – midnight	Terrace door open from 19:30
Wed 11/09	Night-time vent/shutters close	Midnight -7am 21:00 – midnight	
Thu 12/09	Night-time vent/shutters close	Midnight -7am 21:00 – midnight	

Figure 7.6: ultrasonic anemometer (right), pyranometer (left)

Figure 7.7: anemometer at the centre of the window (left), ventilated air temperature and relative humidity sensor, and anemometer mounted on tripod in the centre of the room (right).

Figure 7.8: plans of Casa Batroun and sensors' locations

7.3 Monitoring Results

7.2.1 Aqaba house results

External conditions

a. *Global Solar Radiation on the horizontal plane:* As could be seen in figure 7.9, global solar radiation onto the horizontal plane was consistent during the monitoring period with less than 1.15 % variation in daily solar radiation intensity.

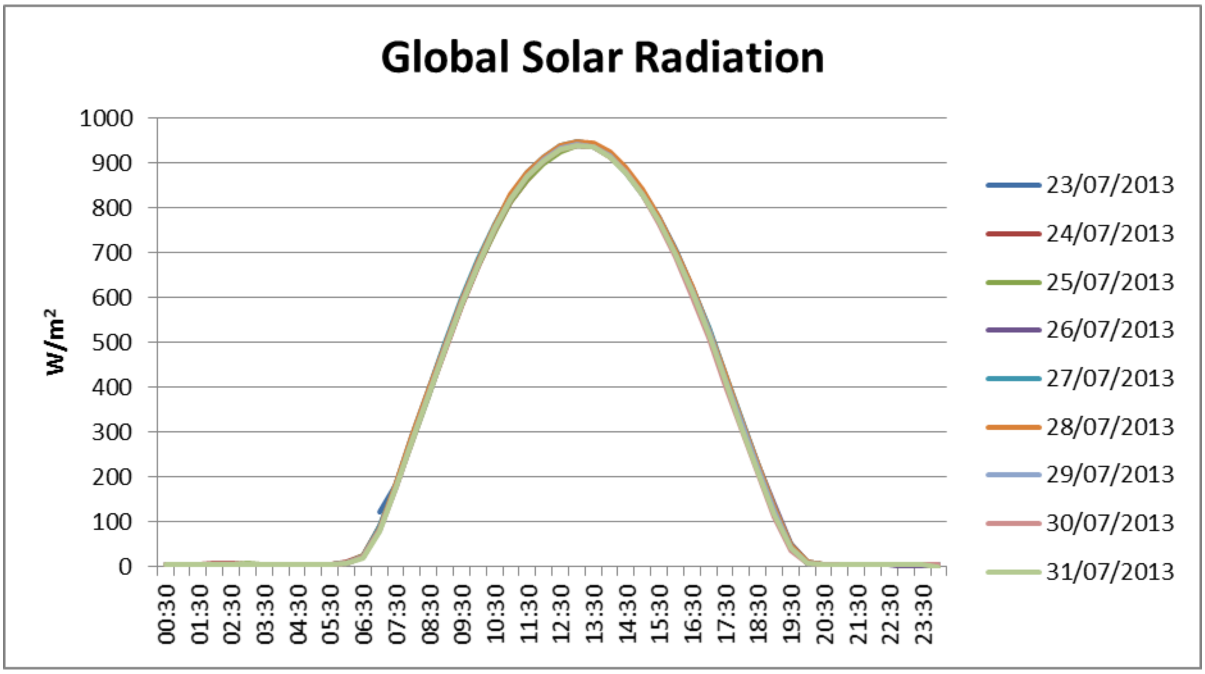


Figure 7.9: recorded global solar radiation onto the horizontal for Aqaba

b. *External Dry bulb temperature DBT:* Two external air temperature measurements were taken; one on the roof at 1m above the floor level and one at the 1st floor terrace/roof garden at 2m above the floor level. The measurements between both sensors varied slightly as shown in Figure 7.11, with variations from day to day measured at the roof level was between 3.2% and 5.8%. The maximum daily monitored temperature ranged between 41.5°C to 44°C and the minimum daily temperature between 26.5°C to 27.2°C, Figure 7.10. The coolest hours of the day were the early morning hours between 04:30-7:00 am and the hottest hours were late afternoon between 16:00-16:30.

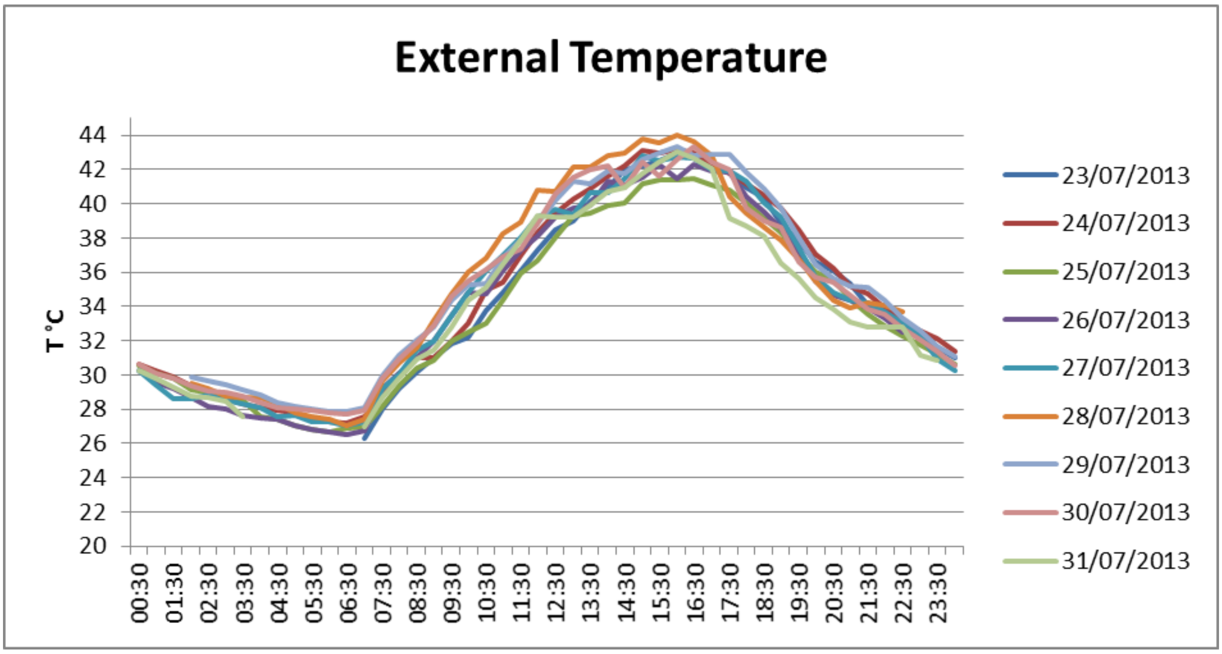


Figure 7.10: External temperature as measured at the roof of Aqaba house

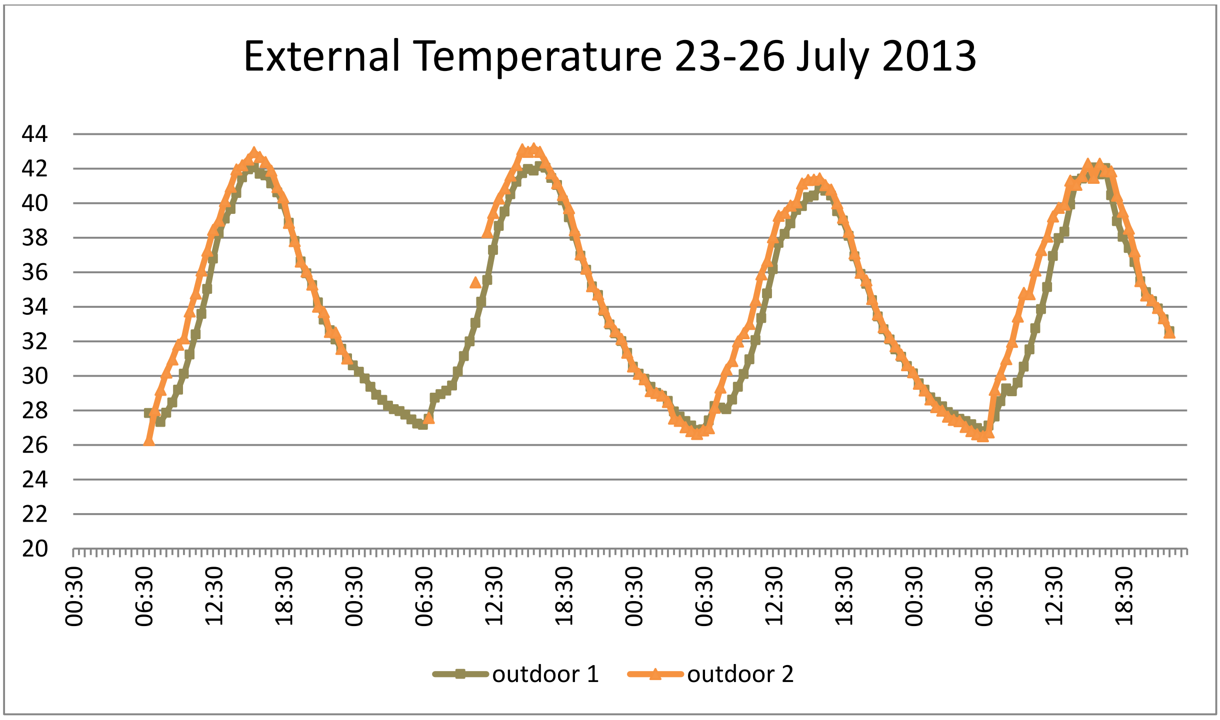


Figure 7.11: External temperature comparison between Outdoor 1: level 1 terrace (roof garden); and Outdoor 2: the roof.

c. *Relative humidity:* As with the DBT measurements the external relative humidity was measured in two locations and varied from 6% to 45% and as expected the RH at 1st floor roof garden level was up to 7% higher than the RH at roof level due to the humidifying effect of plants, Figure 7.12.

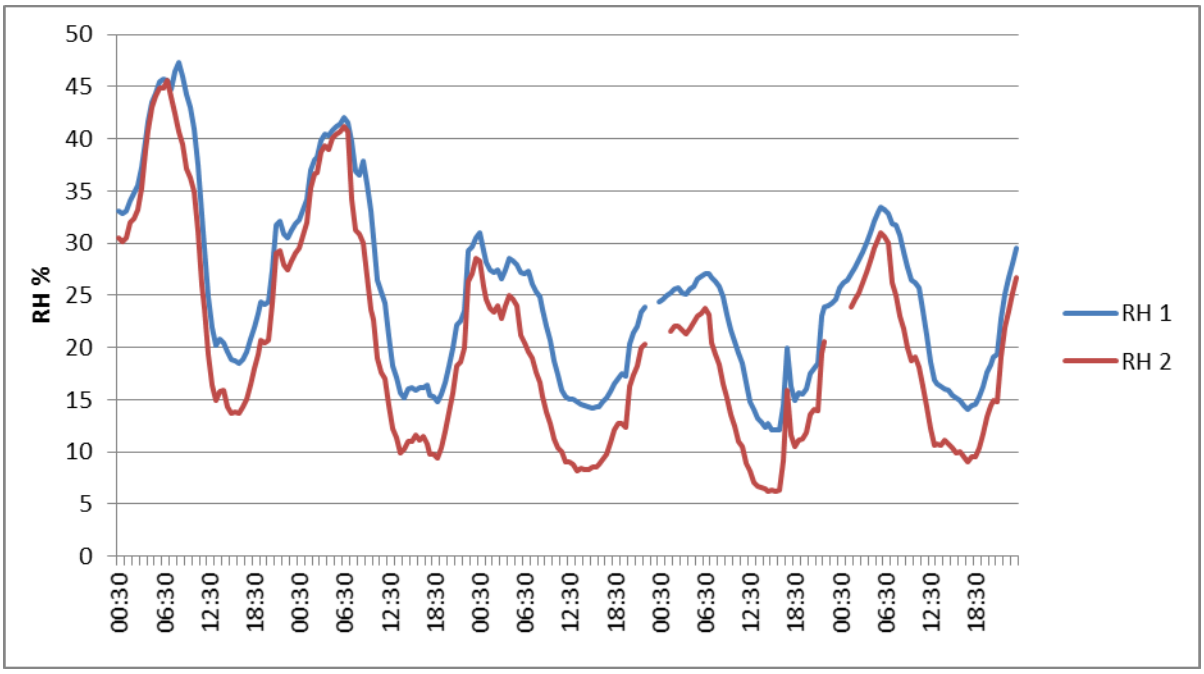


Figure 7.12: External RH, RH 1: on level 1 terrace (roof garden); and RH 2: on the top floor roof.

d. *Wind:* Wind patterns were also consistent with mostly Western to Northern winds at night and Northern winds by day. As for wind speed, early evening winds between 21:00 and 22:00 were the strongest reaching up to 6.8 m/s, compared to the overall average wind speed of approximately 2m/s at night and 4-5 m/s by day.

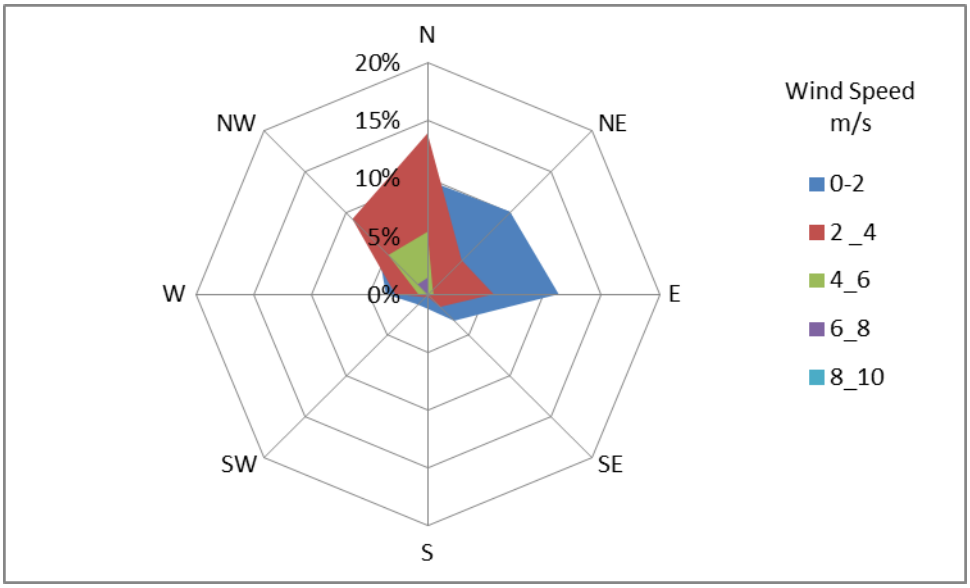


Figure 7.14: wind rose for Aqaba

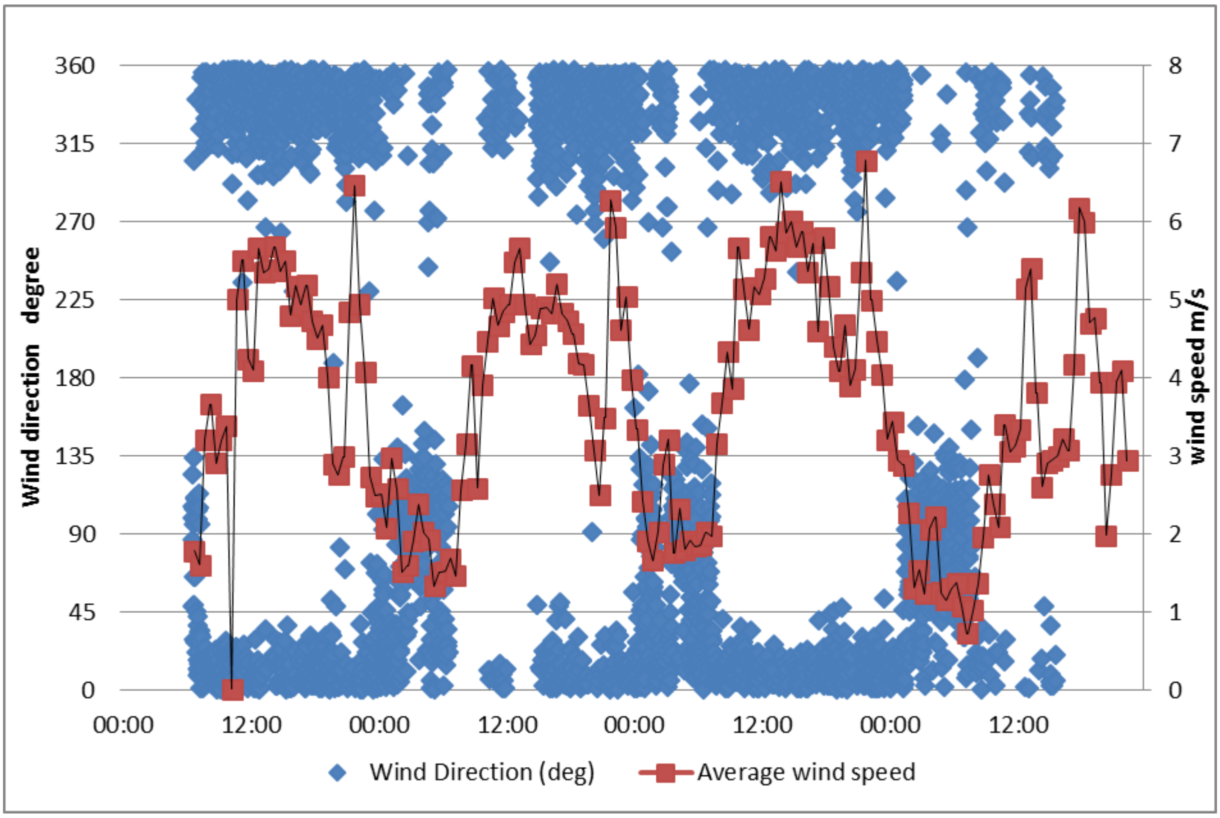


Figure 7.15: wind speed and direction from the 23rd to the 26th of July 2013

e. Comparison of on-site measurements with local weather station data

On-site external weather measurements were compared to available local weather data and forecasts online. Weather Underground website provides historical weather data collected directly from local weather stations monitored by government agencies or international airports. For Aqaba city the closest weather station was Eliat airport weather station.

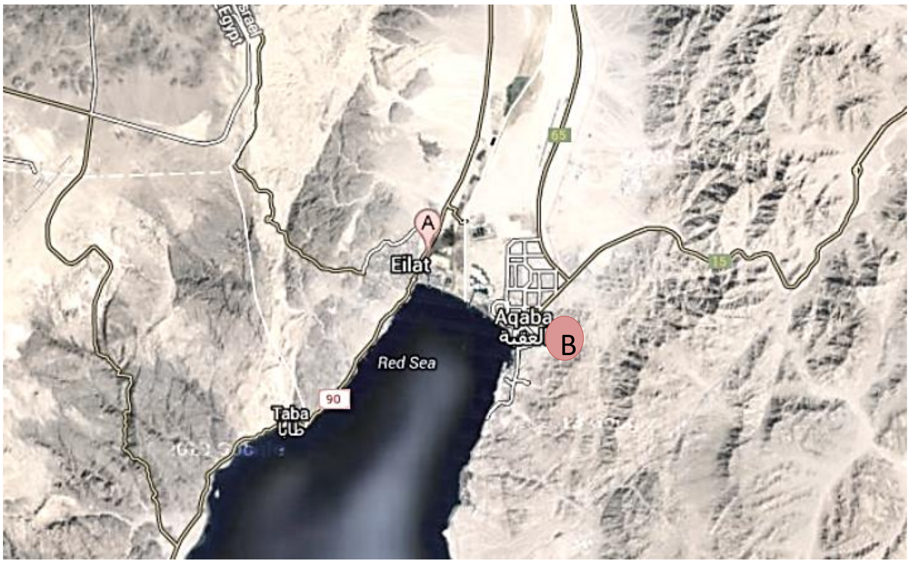


Figure 7.16: (A) Indicates the location of Eliat airport weather station, (B) Aqaba house location

Maximum onsite recorded temperature was compared to maximum temperature recoded at Eliat weather station; on site measurement were found to be always higher than the weather station by 2 to 4K. Minimum onsite recorded temperatures were 0 to 2K higher than the weather station, Figure 7.17.

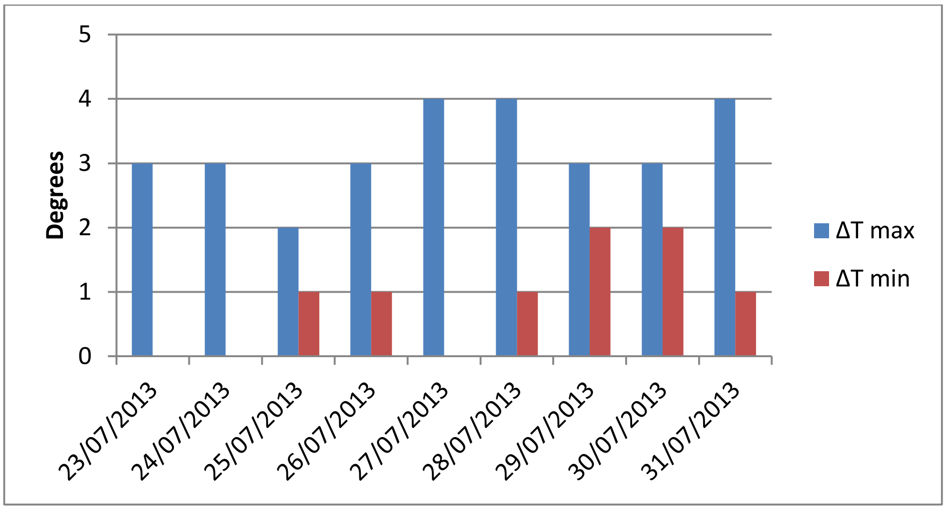


Figure 7.17: Maximum and minimum temperatures difference between on-site measurements and the local weather station, onsite temperatures were up to 4K higher than Eliat weather station.

Maximum onsite RH was +1% to -9% different in value from the weather station, while minimum onsite RH was 8% to -3% different in value, Figure 7.18.

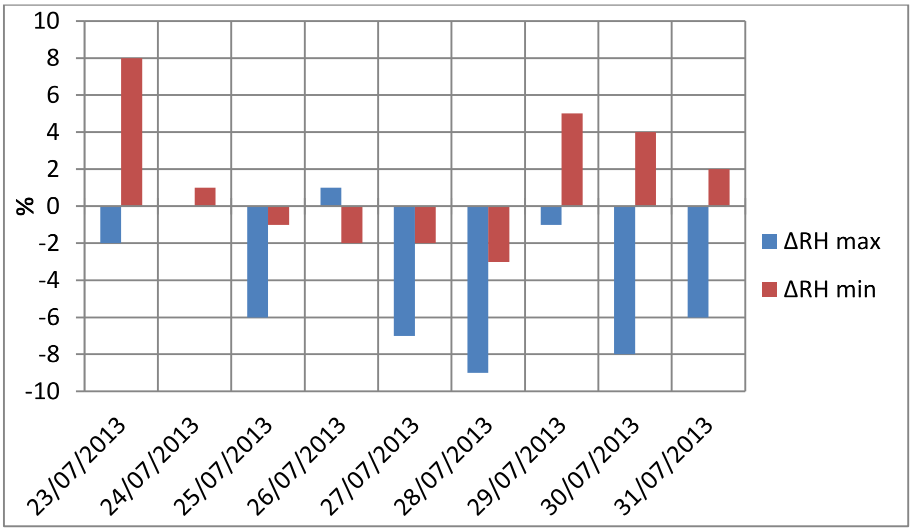


Figure 7.18: Maximum and minimum RH difference between on-site measurements and the local weather station, onsite max RH was up to 9% lower, and min RH 8% higher than the weather station.

Maximum onsite wind speed was -0.5 to +2.6 m/s different in value from the weather station measurements, Figure 7.19.

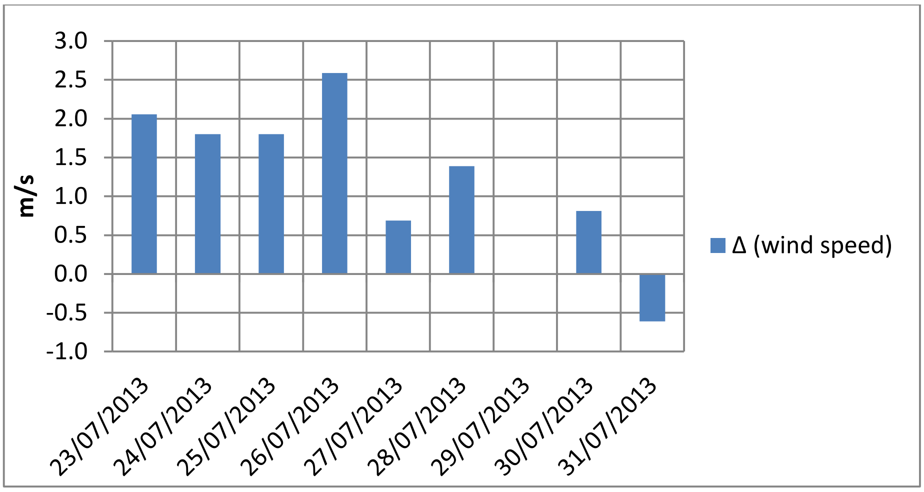


Figure 7.19: Maximum wind speed difference between on-site measurements and the local weather station, onsite wind speed was up to 2.6m/s higher than the weather station.

The differences between the onsite measurements and the weather station can be explained by the distance between the two and the microclimate of the house suburban location.

Internal Conditions

Internal maximum temperatures were up to 6K lower than external maximum with DTV and up to 9K with NTV. The time lag between the occurrence of internal and external peak temperatures in NTV was up to 4 hours. The peak daily external and peak daily internal temperatures in all rooms are shown in Figure 7.21

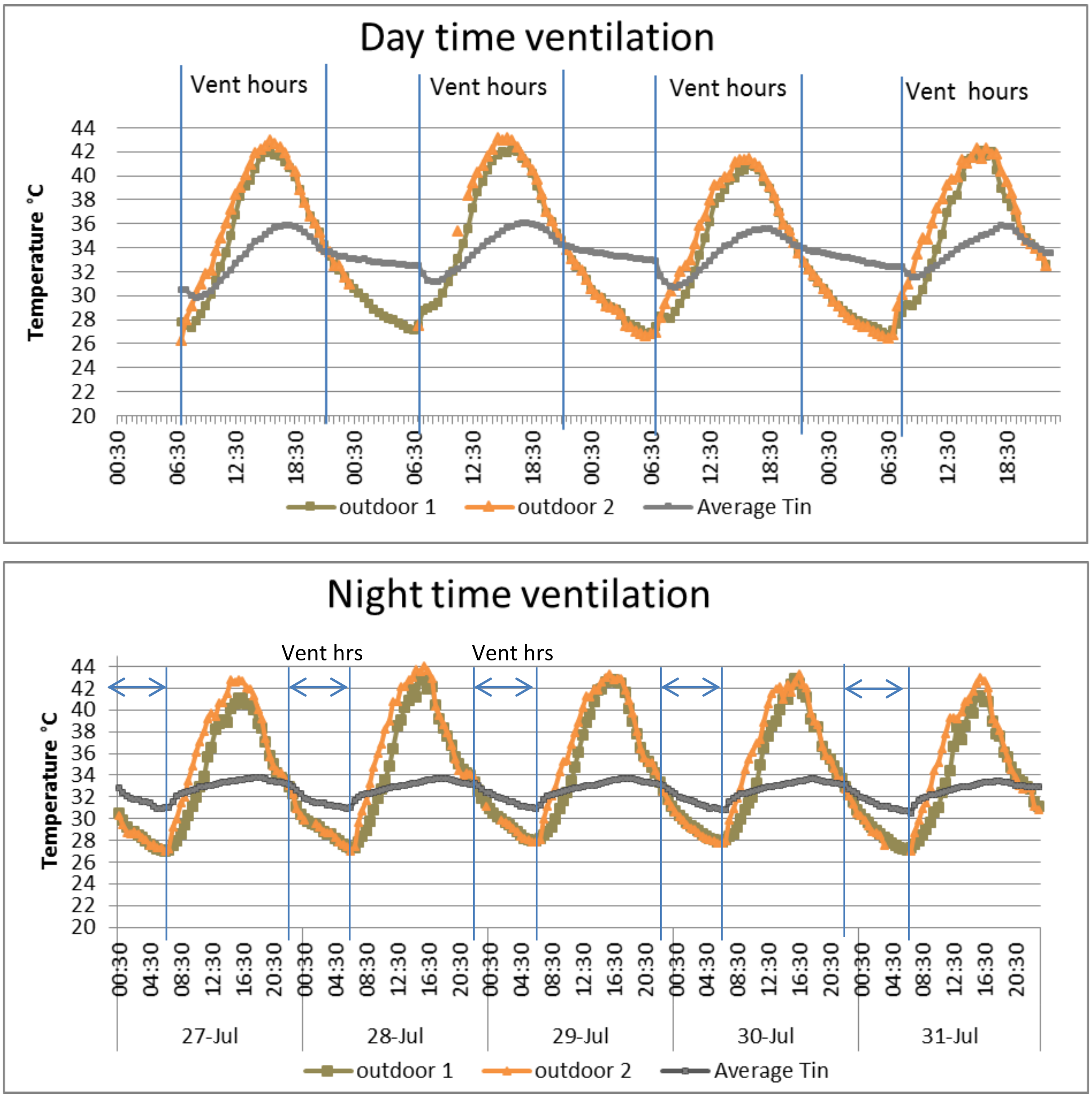


Figure 7.20: measured average internal temperature compared to external temperature in Aqaba house for Dtv (top) and NTV (bottom)

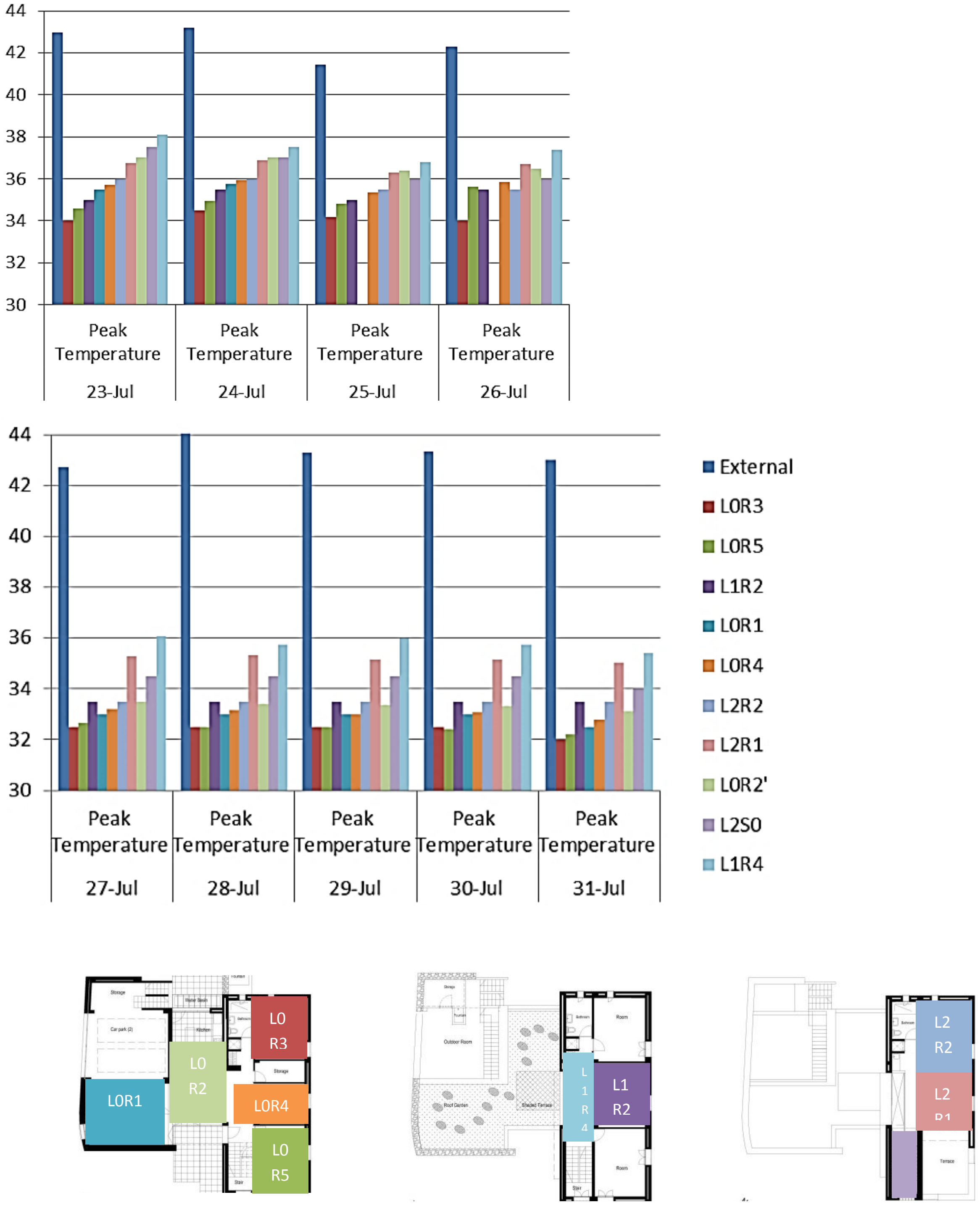


Figure 7.21: peak temperature in all rooms in Aqaba house, DTV (top), NTV (bottom).

To quantify and compare the overall performance, an index debriding the difference in internal and external temperature, over the period of the day where the external temperature is higher, and takes into account the length of this time period, was developed. The index, called Kelvin Hour Reduction (or Khr), can best be appreciated graphically, as illustrated in figure 7.22. The reductions in Kelvin degree hours (Khr) between internal and external temperatures were calculated and are shown in figure 7.23, with higher values of Kelvin degree hours indicating better ventilation/cooling performance. The Kelvin hour reduction (Khr) is the shaded area as illustrated in figure 7.22, i.e. the product of the difference in temperature between inside and outside and the duration of this difference (0.5 hours). For example, T_{in} was lower than the external temperature by 2K for 0.5 hours then by 2.5K for the next 0.5 hours, (2*0.5) + (2.5*0.5) =1.65 Khr reduction in temperature from external levels at this one hour of time. Figure 7.23 compares DTV and NTV scenarios.

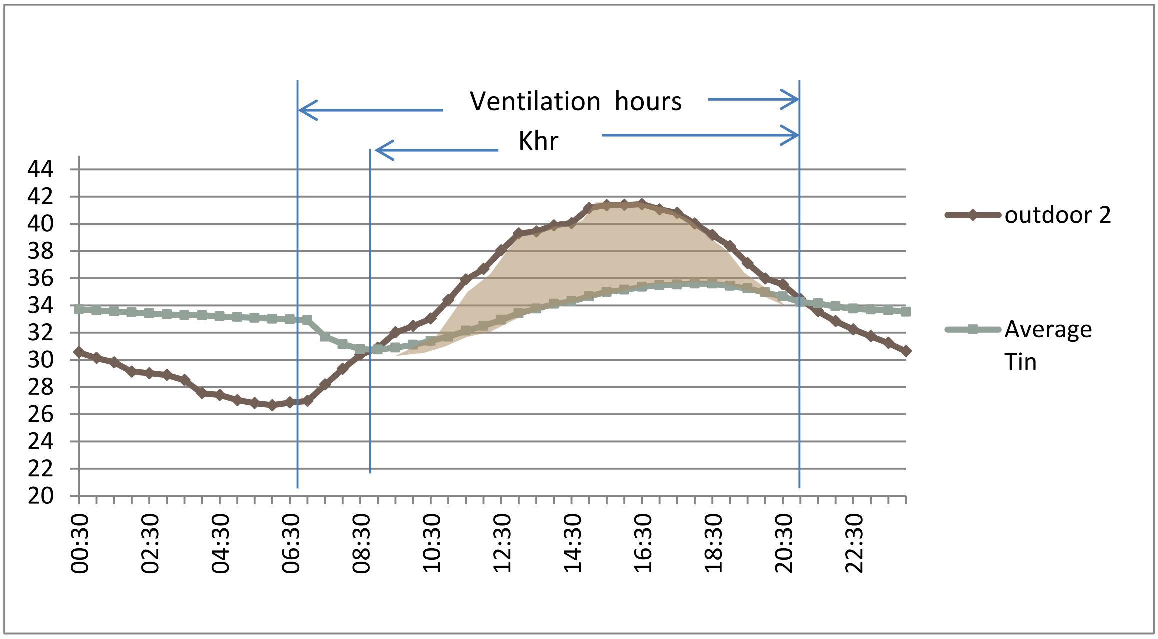


Figure 7.22: the concept of Kelvin hours reduction (Khr)

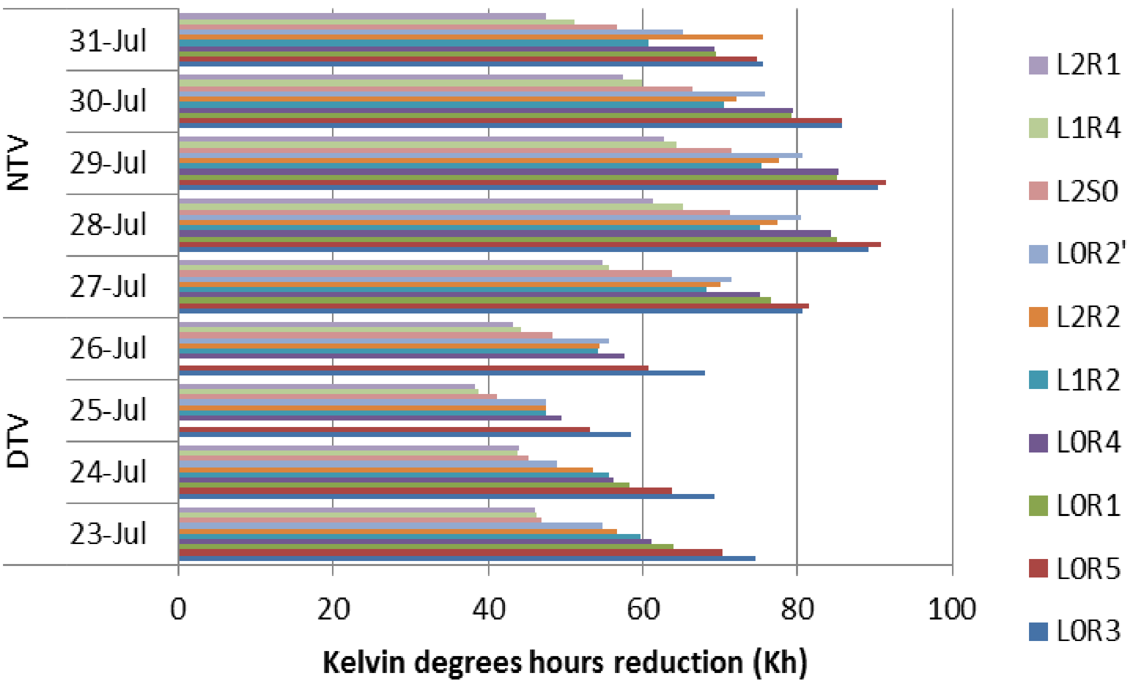
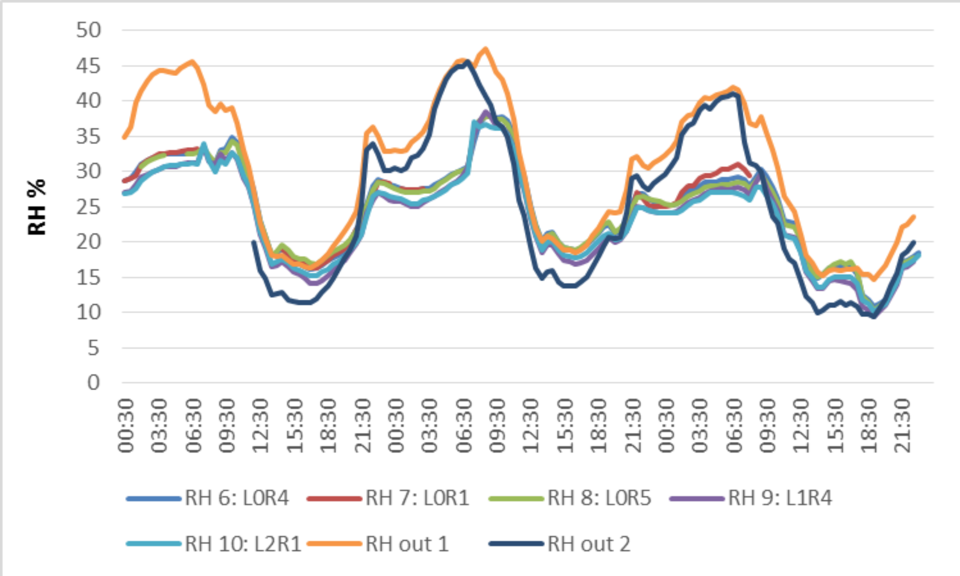


Figure 7.23: Kelvin degree hour reduction from external temperature levels, DTV, NTV average Khr=53.2Kr, 72Khr respectively, a 36.8% increase from DTV.

As for internal RH, it followed external levels closely during ventilation periods but there was a discrepancy up to 10% when windows were closed during both ventilation scenarios. Very little variation was observed from room to room as shown in Figure 7.24.



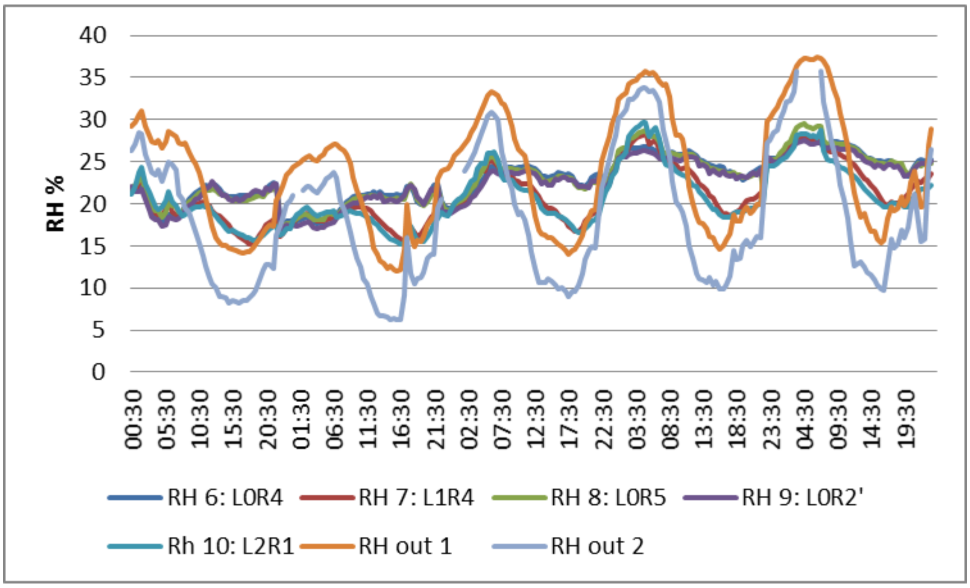


Figure 7.24: relative humidity, DTV (top) NTV (bottom)

Air velocity measurements in the middle of rooms showed very minimal air movements except for L0R2 which had a north facing opening with no Venetian shutters (a terrace door). Figure 7.25 shows the airspeed in rooms L2R2, L0R5, and L0R2, all north facing, and L1R4, a south west facing room. Similarly to L0R2, L1R4 had a terrace door without Venetian shutters. Recorded airspeed in the rest of the rooms was 0 m/s. Terrace doors in L0R2 and L1R4 were closed in NTV mode for security reasons, the resulting internal air speed at night was below 0.1m/s at all times in all rooms.

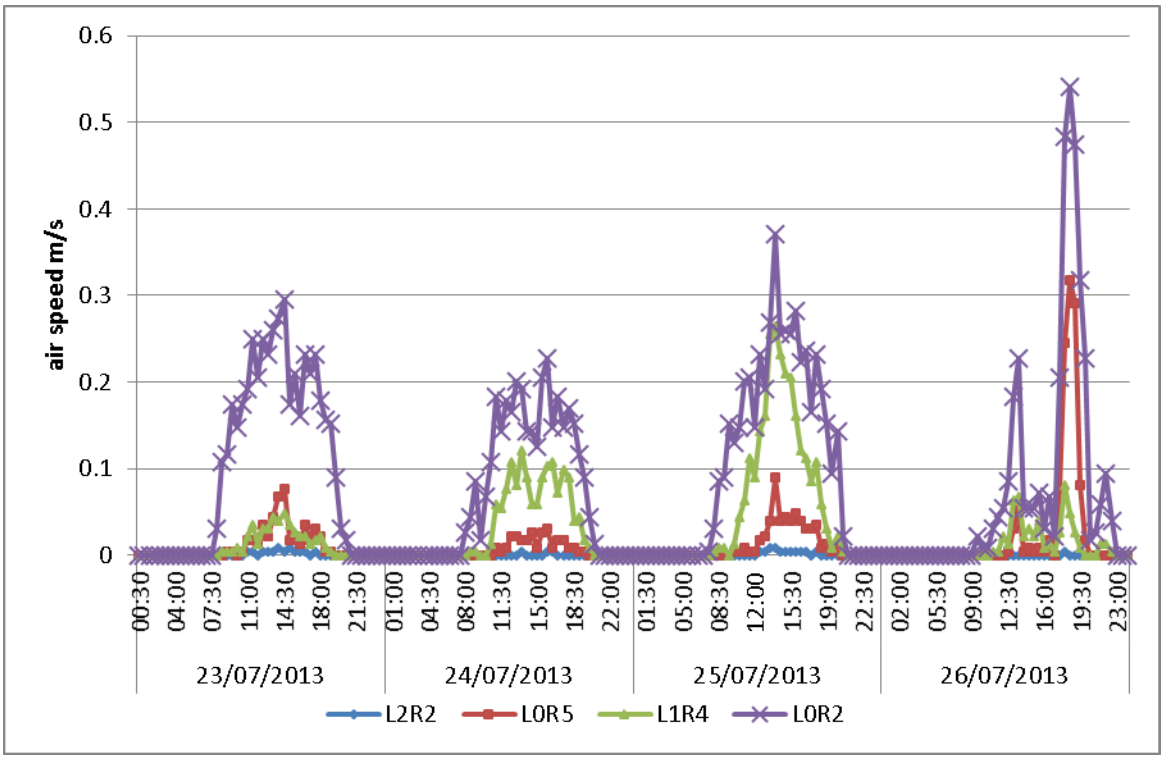


Figure 7.25: Recorded air velocity in all rooms during DTV

7.3.3 Casa Batroun

External conditions

a. *Global Solar Radiation on the horizontal plane:* As could be seen in Figure 7.26, global solar radiation on the horizontal plane was less consistent during the monitoring period than in Aqaba city; however with the exception of the 4th of September, which was a cloudy day, the daily peak solar radiation varied by less than 5%, between 830 W/m^2 and 800 W/m^2

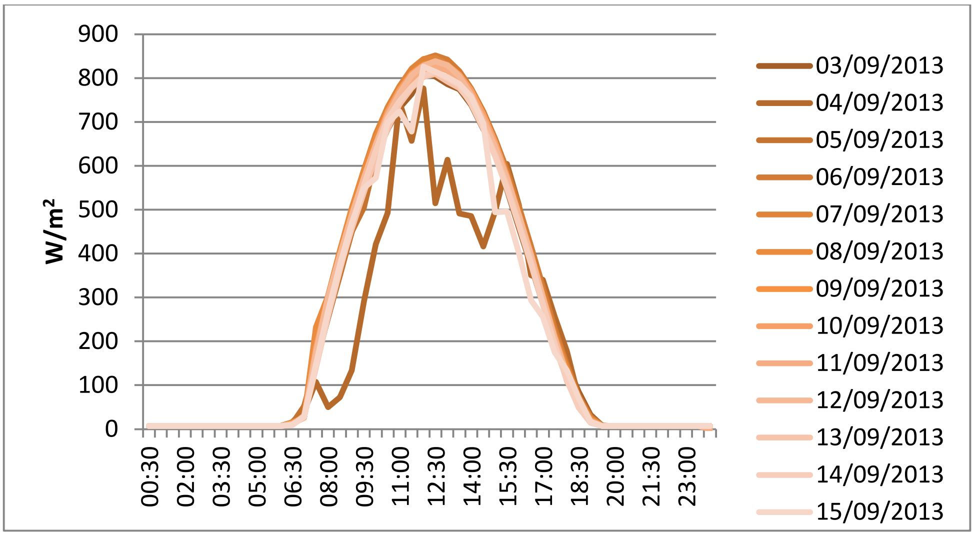


Figure 7.26: solar radiation onto the horizontal for Casa Batroun

b. *External temperature*: Only one sensor recorded external air temperature in Batroun, more variation in external temperature is observed in the coastal region of Batroun. The daily peak DBT ranged between 31°C to 36°C, and the daily minimum DBT between 21°C to 26°C. Similarly to Aqaba, minimum temperatures occurred in the early morning hours, however, maximum temperatures occurred around mid-day at 13:00, Figure 7.27

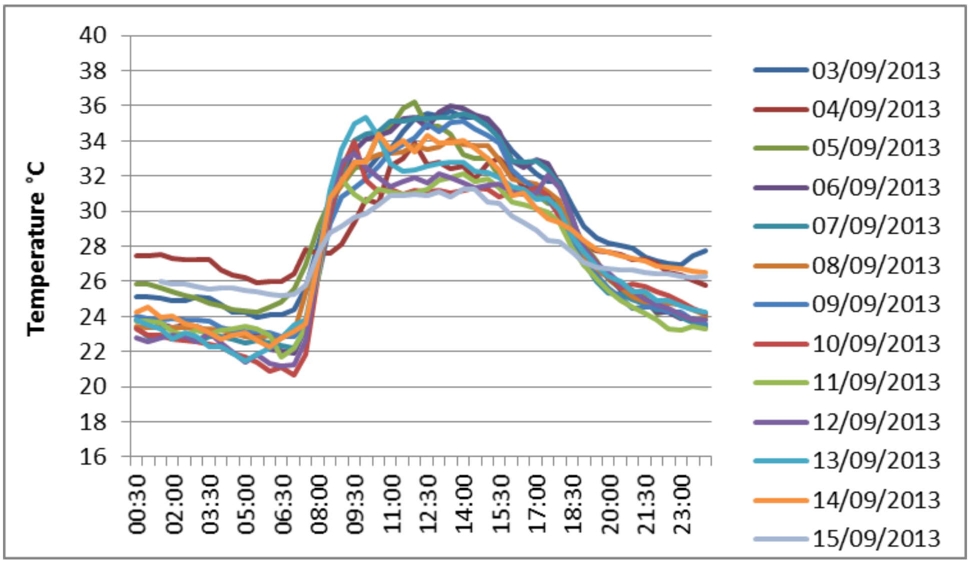


Figure 7.27: measured DBT for Casa Batroun

c. *Relative humidity*: RH was very high at night, up to 85% but sometimes dropped to as low as 35% at noon, Figure 7.28.

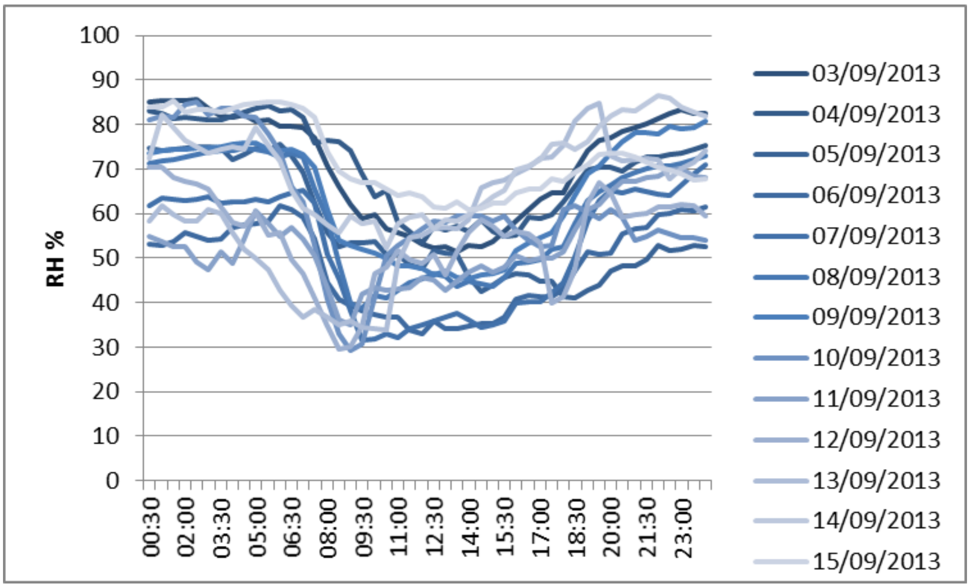


Figure 7.28: measured RH for Casa Batroun

d. *Wind*: the prevailing wind was South-eastern at night and western during the day,

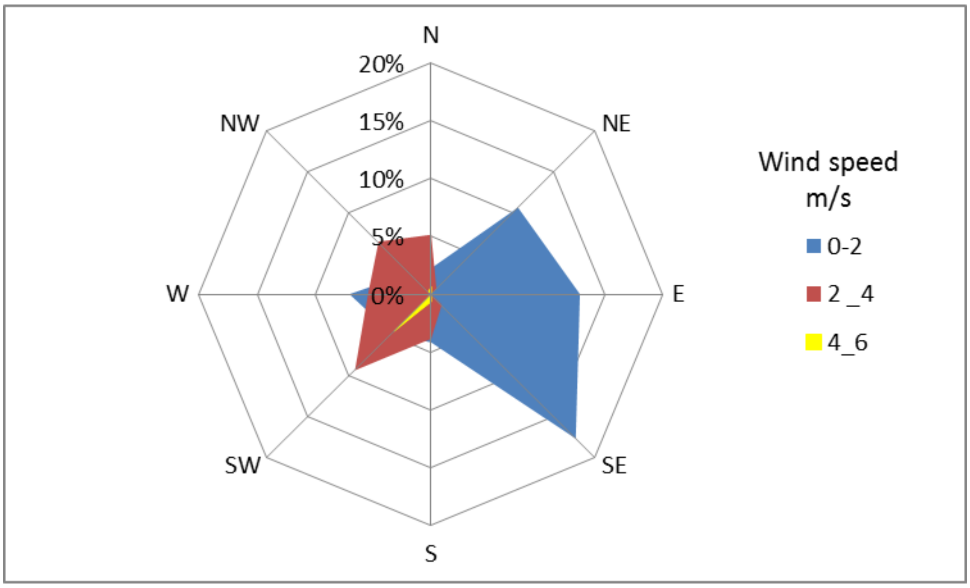


Figure 7.29: wind rose for Casa Batroun

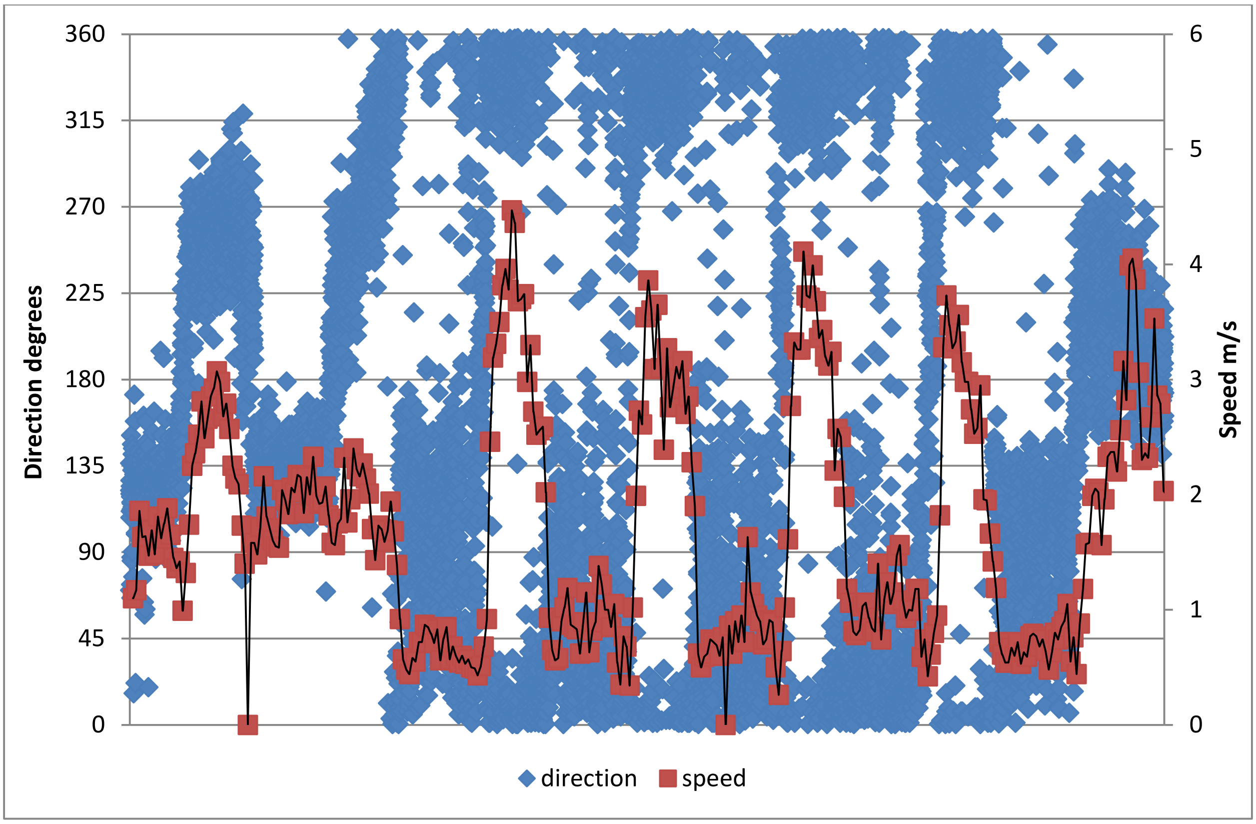
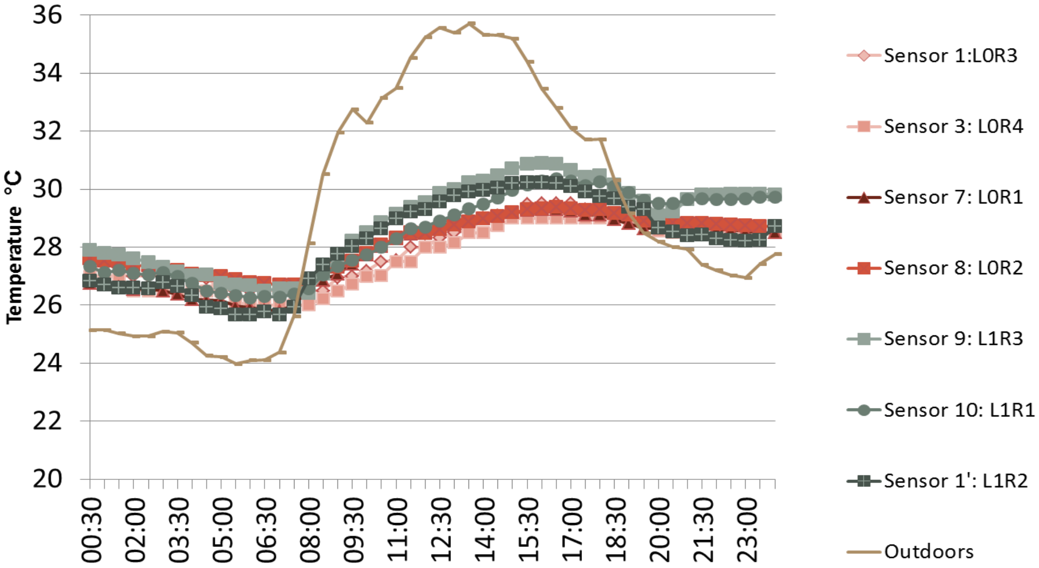


Figure 7.30: Wind speed and direction from 3rd to 10th of Sep

It wasn't possible to compare the measurement of outdoor weather variables with a nearby weather station as the nearest weather station was about 55.2 km away from the site.

Internal conditions

Similar observations to Aqaba house were made. However, more interestingly the performance of the two different floors differed significantly. Temperatures in the top flat were higher than the ground floor flat, (shown in figure 7.31), because; a) the ground floor was better shaded by nearby trees and adjacent buildings, b) the 1st floor had a higher exposed surface area resulting in additional solar gains through the roof, and, c) the effect of the ground floor's higher thermal mass in storing coolth was more noticeable with NTV, where day time internal temperatures remained only 2K.



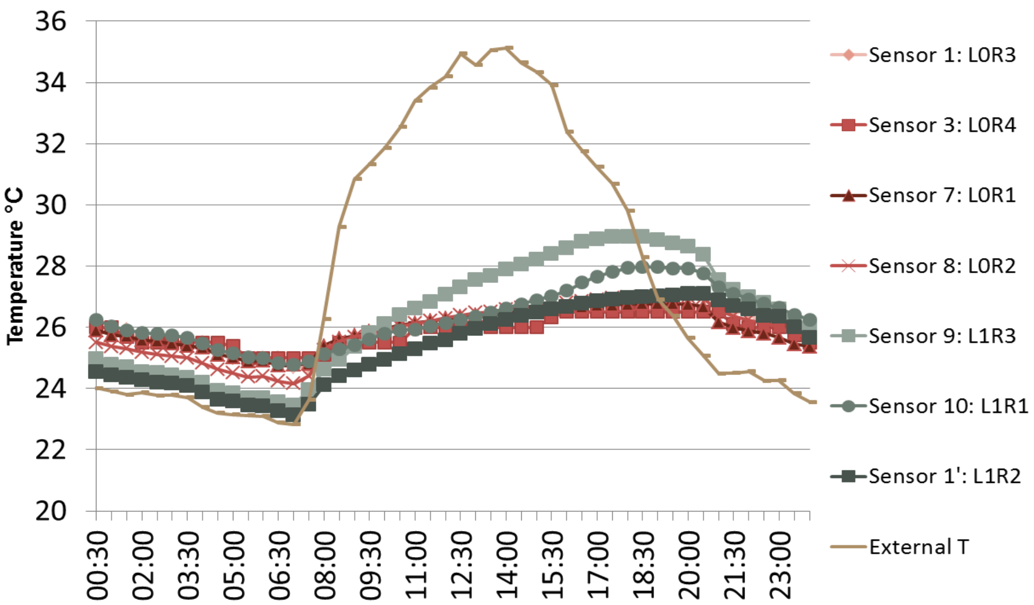


Figure 7.31: internal and external temperature for DTV (top) and NTV (bottom).

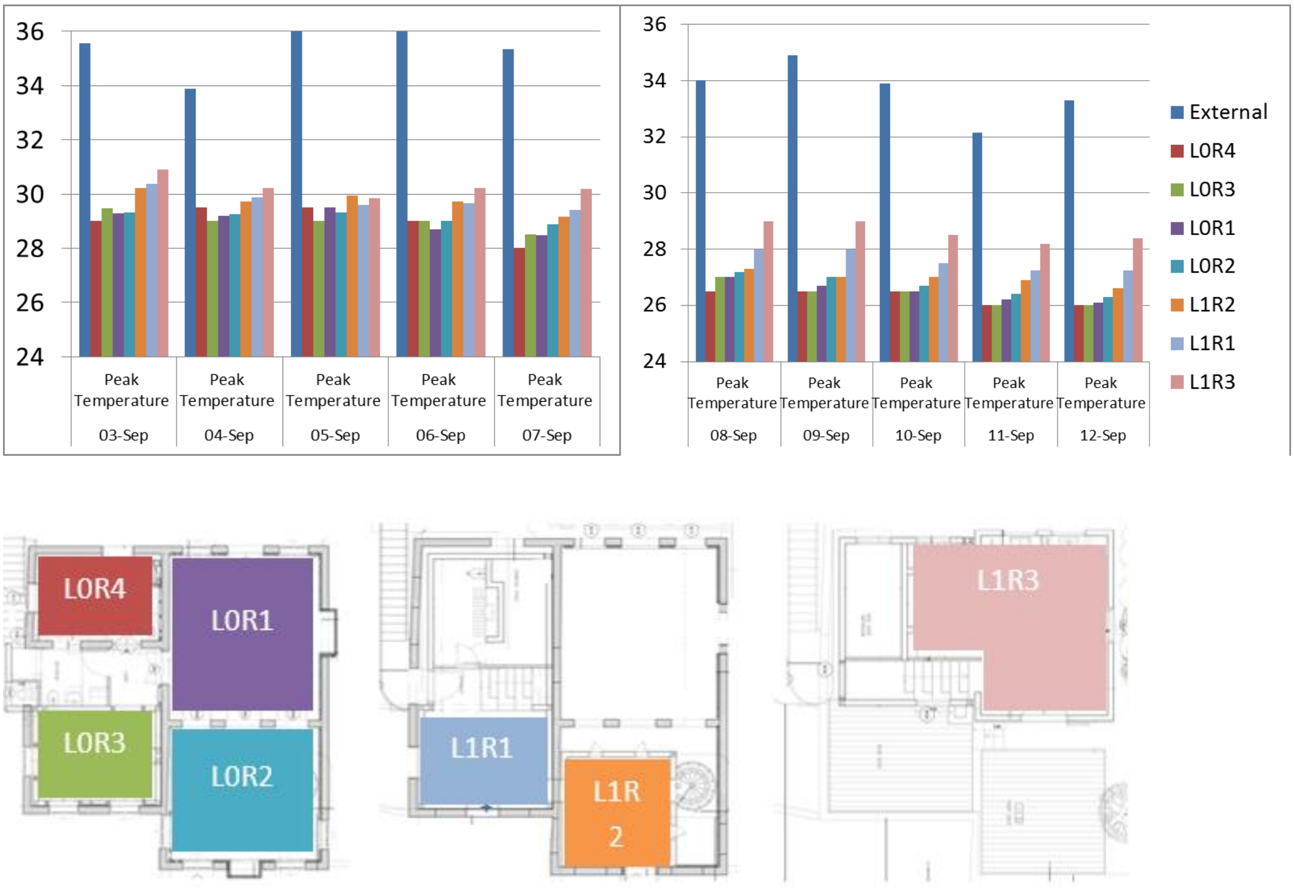


Figure 7.32: internal peak temperatures for DTV (left); NTV (right).

Kelvin hour reduction was also calculated as shown in Figure 7.33.

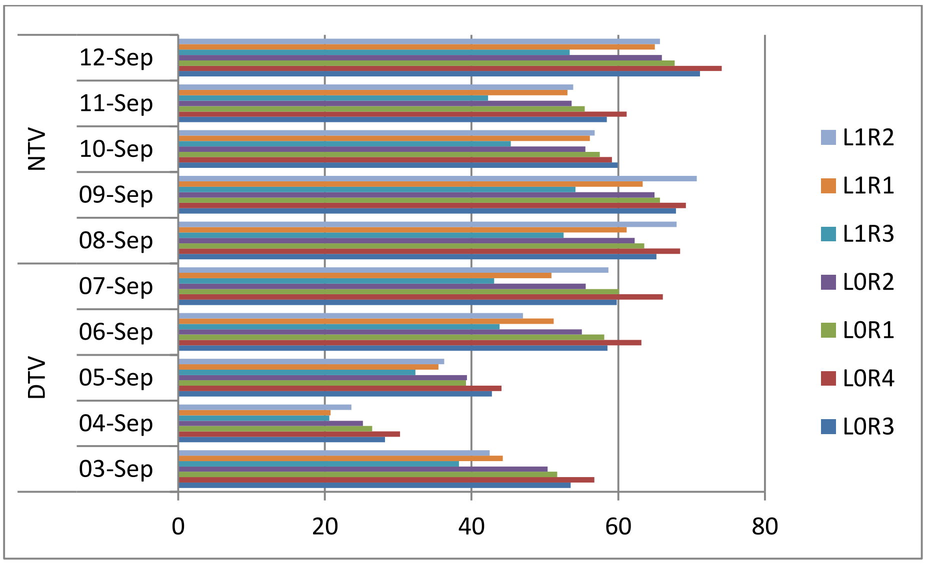


Figure 7.33: Kelvin hour reduction from external temperature levels, DTV, NTV average KhR=44.5Kh, 61Kh respectively, 37% increase.

Recorded air velocity in the middle of the rooms that had Venetian shutters was minimal, while a maximum of 0.4m/s was recorded in room L1R3 that had an open terrace door with no shutters. Such low air velocities mean that relying on naturally driven air movement to provide cooling sensation for occupants was not possible.

7.4 Summary

The maximum internal temperatures in both buildings were between 4°C to 6°C below maximum external levels in the DTV scenario, while NTV resulted in up to 9°C reduction in the internal peak temperature from maximum external temperatures.

The maximum recorded internal temperature in the Aqaba house was between 34°C and 38°C for DTV and 32°C to 36°C for NTV. While in Casa Batroun the internal temperature was between 28°C to 31°C in the DTV scenario and 26 to 29°C in the NTV scenario. With the exception of the latter case, and despite the recorded temperatures being several degrees below external temperature in all scenarios, they were mostly still above the upper comfort limit. This is in line with the findings of Chapter 5 (Figure 5.45) where DTV and NTV were not recommended for the very hot-dry zone in July and August, and NTV was highly recommended in the hot humid zone in September.

Variations in internal temperature across all rooms in the Aqaba house could be attributed to higher solar gains, because rooms that had no Venetian shutters exhibited the highest internal temperatures. In the Casa Batroun house the reasons behind the variation could be attributed to higher solar gains as well as the construction type.

7.5 Monitoring limitations

The monitoring of internal temperature and relative humidity as well as external weather conditions helped to understand the real potential of DTV and NTV scenarios in the very hot arid climate of Aqaba and the warm-humid climate of Batroun. These measurements were used in Chapter 8 to compare the actual potential of NTV and DTV to that predicted by dynamic modelling in previous chapters. However, they cannot be used for validation of the model, mainly because no air flow rate or pressure measurements around the façades were taken;

meaning that it was not possible to validate the predicted air flow rates in IES with the real case scenario. This was the main limitation of the monitoring study. Gas decay tests for air flow measurements were difficult to conduct in the studied houses for several reasons, mainly the difficulty in transporting the necessary equipment for the test to Jordan and Lebanon or obtaining this equipment in the studied countries, in addition to the large scale of the studied houses.

Air velocity measurements were taken in the centres of rooms because the main interest was to establish the likely air speed within the rooms and whether it was sufficient to provide a cooling sensation. However, where possible measurements of air velocity at the centre of windows were taken, and were then used to estimate the flow rate through these windows in Chapter 8. Nonetheless, it is acknowledged that these measurements were not reliable because the rotating cup anemometers used were not capable of measuring very low air velocities. A study by Levermore et al., (2001) showed that the rotating cup anemometer was very inaccurate when the wind speed fell below 3 m/s. Their study had also shown that the rotating cup anemometer indicated zero wind speed over many hours in a day, due to the inertia and friction of the cups, although speeds of up to 1.5 m/s were recorded by an ultrasonic anemometer.

The ultrasonic anemometer used for measuring external wind speed and direction was fixed on a tripod and aligned manually with the help of a digital compass until it faced north, however, as this was done manually, visual errors were possible, and could have resulted in the wind direction measurements being incorrect by several degrees.

There were also some missing temperature and RH measurements, sometimes up to a few hours, especially when windows were closed, because the signal transferred to the data-logger was blocked by the thick walls.

Another limitation of the study was that the houses' occupancy was limited to few hours of the day by a maximum of two people. This meant the reduction in peak internal temperatures in the monitored buildings could be expected to be less than recorded in this study when the buildings are fully occupied.

Chapter 8: Monitoring Vs Modelling

8.1 Comparison with the model

In order to compare the simulations against the monitored data, both buildings (Aqaba and Casa Batroun) were modelled again but with edited weather files and occupancy profiles. The new weather files included onsite measured weather variables, DBT, RH, wind speed and direction and global solar radiation. Diffuse and direct normal radiation were calculated from the monitored data and included in the new weather files. Both monitored buildings were unoccupied for the majority of the time, but in durations where there was periods of limited occupancy, this was recorded and reflected in the model. Weather files used in the simulation were edited using 'epw creator' software.

Despite editing the weather files and occupancy profiles, several discrepancies were noted between the modelled and the monitored results. In the case of Aqaba house, the modelled internal temperatures were several degrees higher than recorded (Figure 8.1). Although NTV results agreed better with measured results, it seemed that the model was more sensitive to external air temperature than the monitored building.

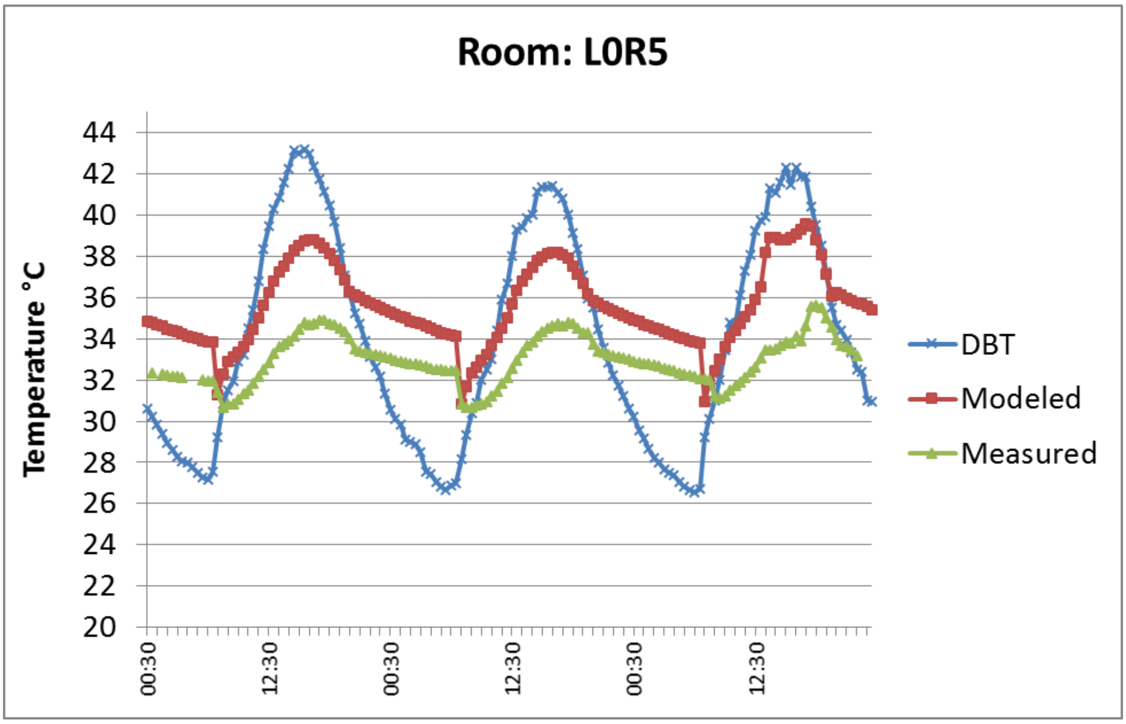


Figure 8.1: DTV measured and modelled results in Aqaba house, room L0R5

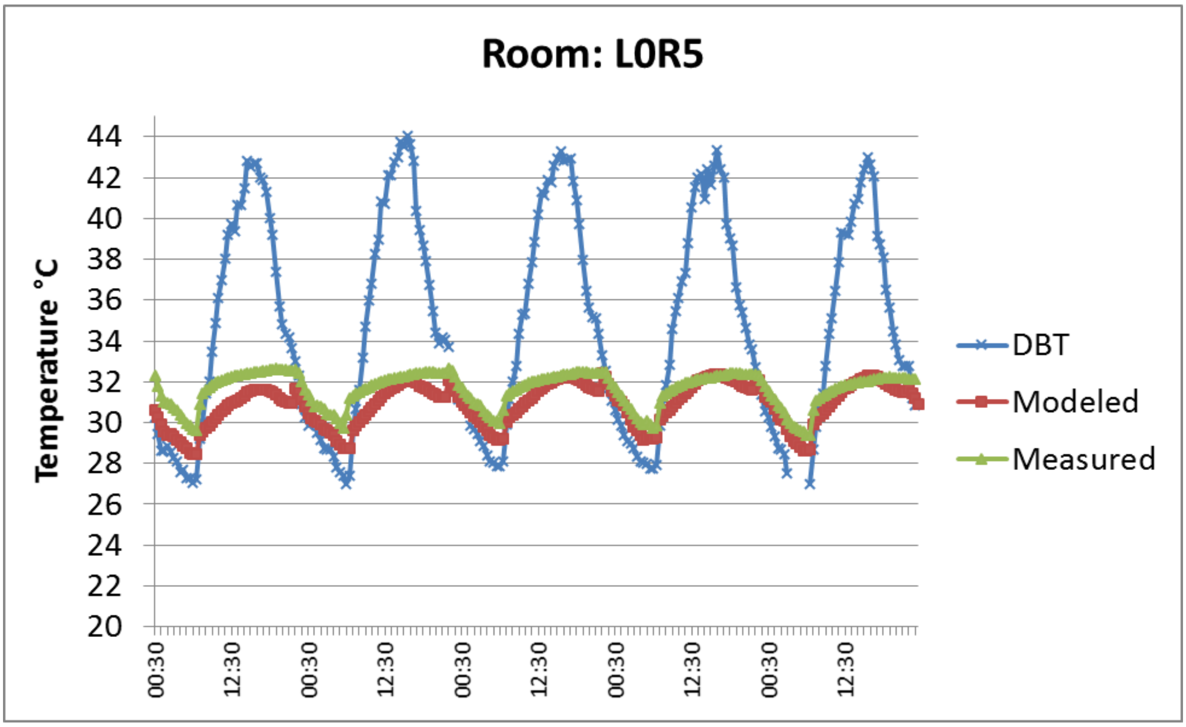


Figure 8.2: NTV measured and modelled results in Aqaba house, room L0R5

Similar observations were made in Casa Batroun where predicted internal temperatures were several degrees higher than in the monitored DTV, while NTV agreed better for both floors, Figures (8.3 & 8.5) and Figures (8.4 & 8.6), respectively.

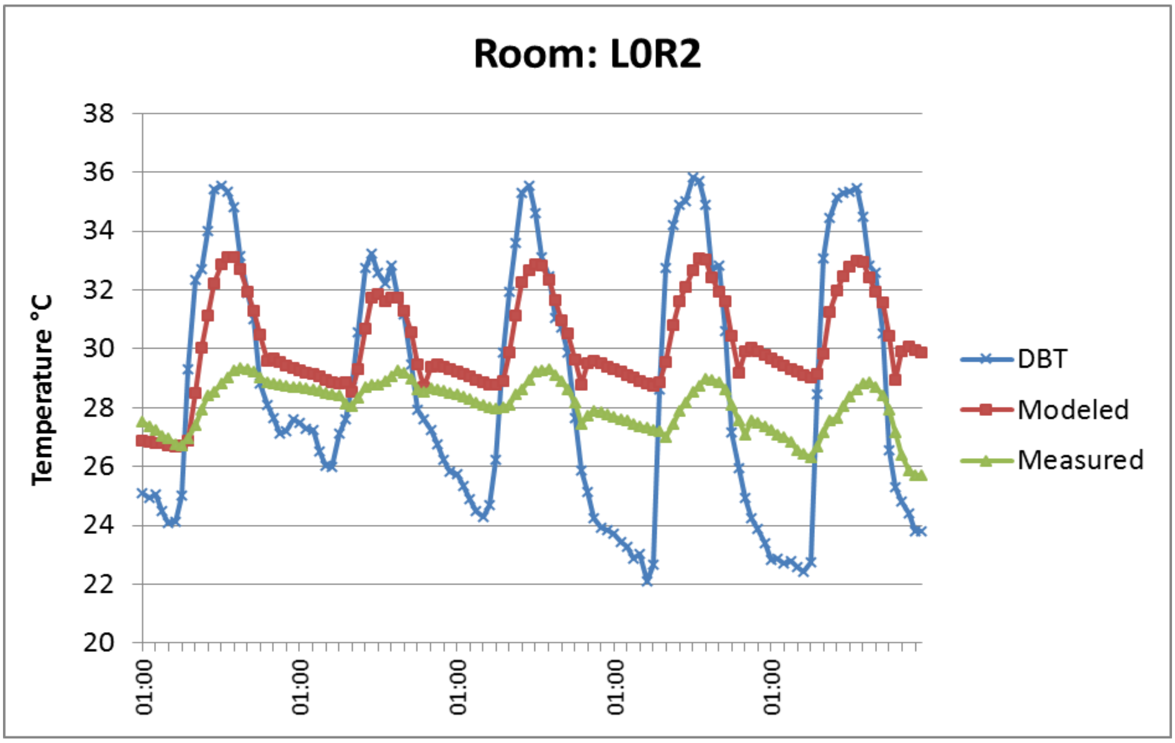


Figure 8.3: DTV measured and modelled results in Casa Batroun, ground floor.

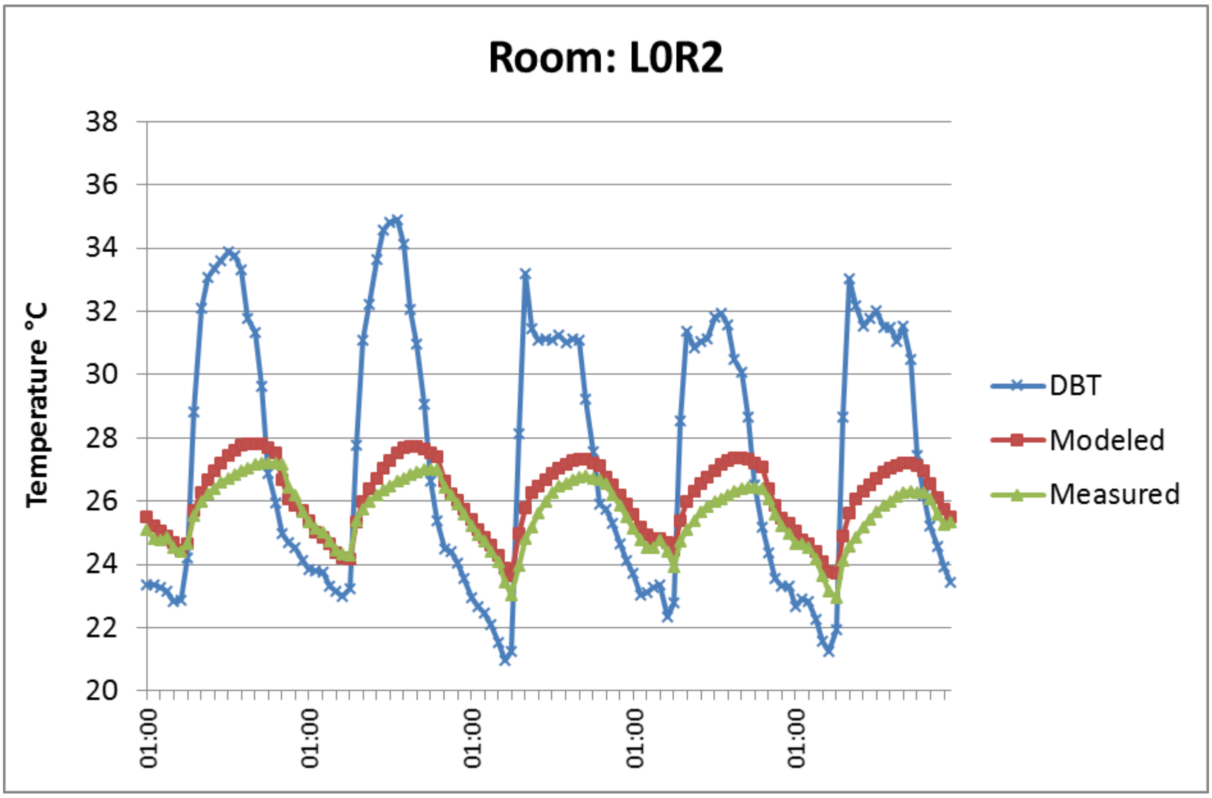


Figure 8.4: NTV measured and modelled results in Casa Batroun, ground floor.

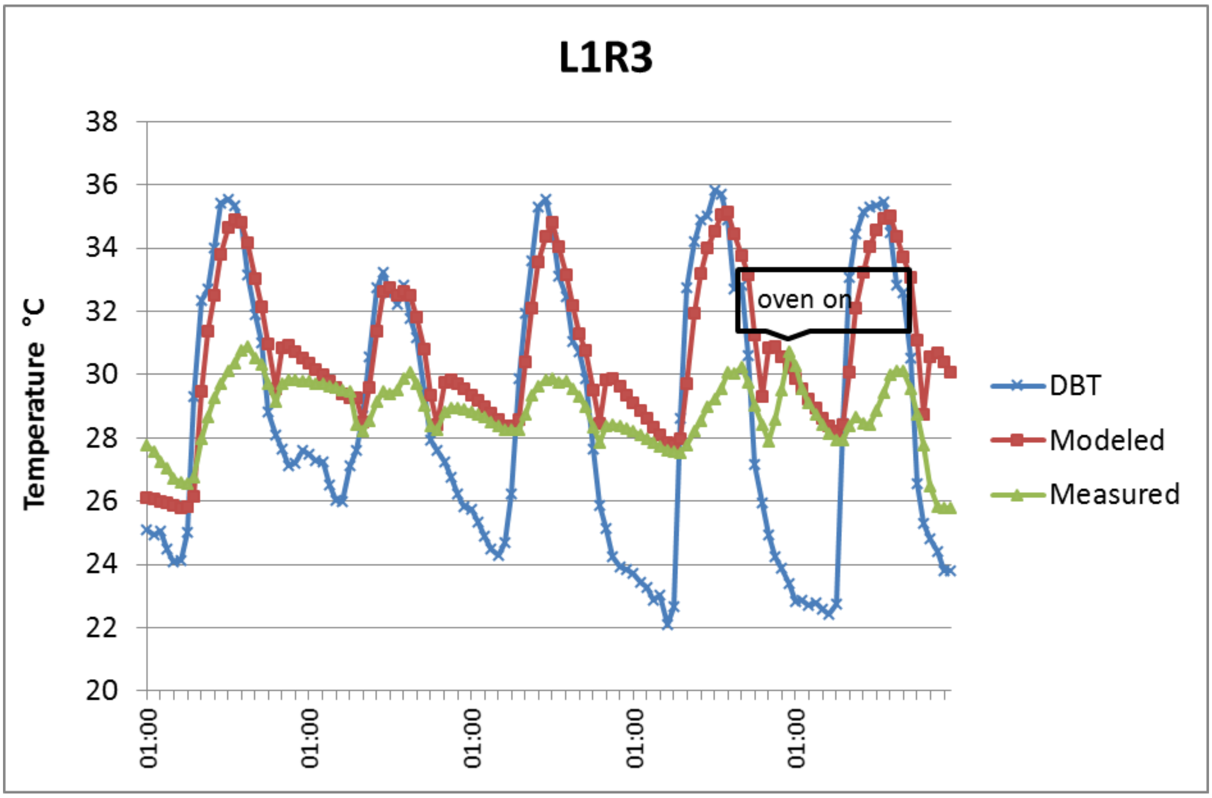


Figure 8.5: DTV measured and modelled results in Casa Batroun, 1st floor.

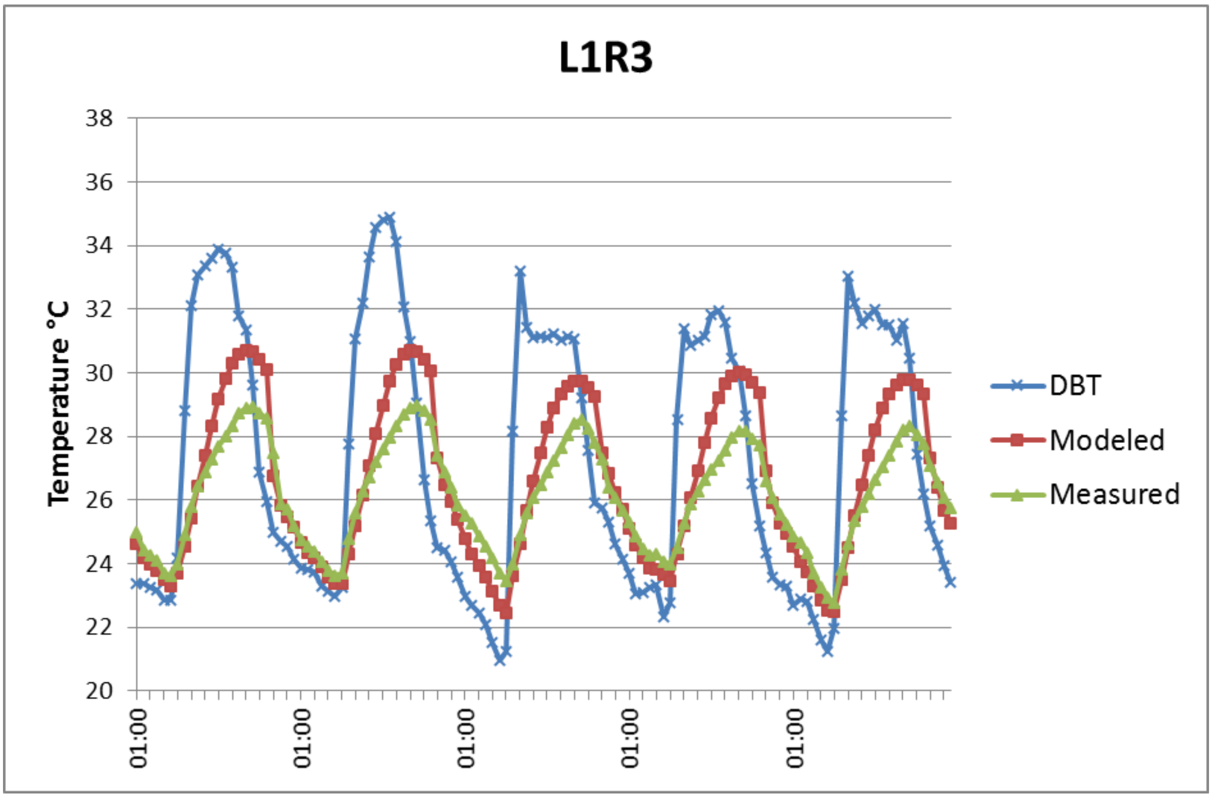


Figure 8.6: NTV measured and modelled results in Casa Batroun, 1st floor.

8.2 Discussion on the possible reasons behind the discrepancy

In addition to the limitations of the monitoring as discussed in section [7.7] that contributed to inaccuracies in the monitored results, other factors related to shortcomings in the model may have contributed to the discrepancy between modelled and monitored results.

False representation of louvered windows (open windows with closed Venetian shutters) would result in the model over-predicting ventilation rates and consequently over-predicting internal temperatures. A study by Coley (2008) on how top hung windows were represented in IES found that the ventilation rate depends to a great extent on how the windows were represented, whether as a vertical "arrow slit" hole in the wall or as a horizontal "letter box" opening. Inaccurate representation was found to result in airflows up to four times higher. Although IES provides an option for windows with louvers, their representation is not clear. Additionally, the discharge coefficient of the windows was not known, though the sensitivity analysis conducted in Chapter 5 showed that this parameter had little impact on the overall overheating hours during hot months. However, the uncertainty analysis of discharge coefficient was repeated for the new case with edited weather files and occupancy profiles.

Four cases were studied with C_d of 0.4, 0.3, 0.2 and 0.1. For every 0.1 reduction in C_d, a reduction of approximately 25% was achieved in air change rates per hour for the house. However, not even the lowest flow rates achieved (Figure 8.7) brought the predicted internal temperatures significantly closer to the measured ones.

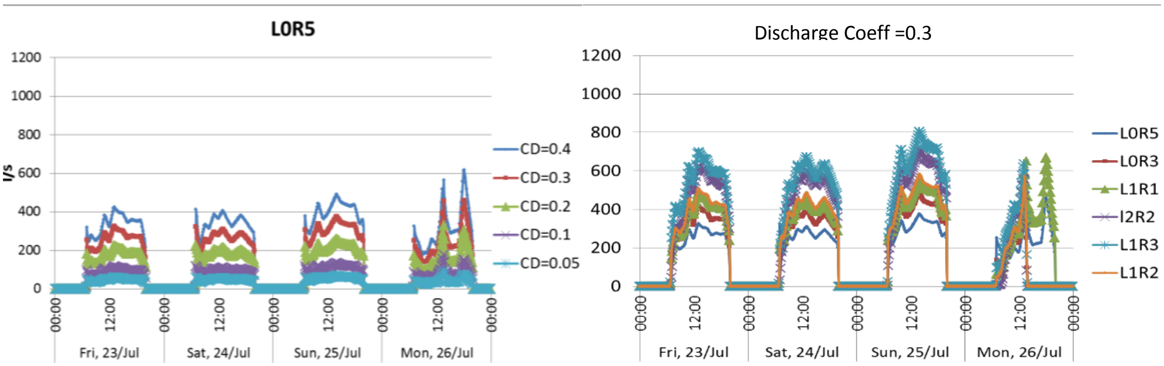


Figure 8.7: Aqaba DTV airflows l/s in L0R5 (left), air flows in all rooms l/s for C_D = 0.3 (right).

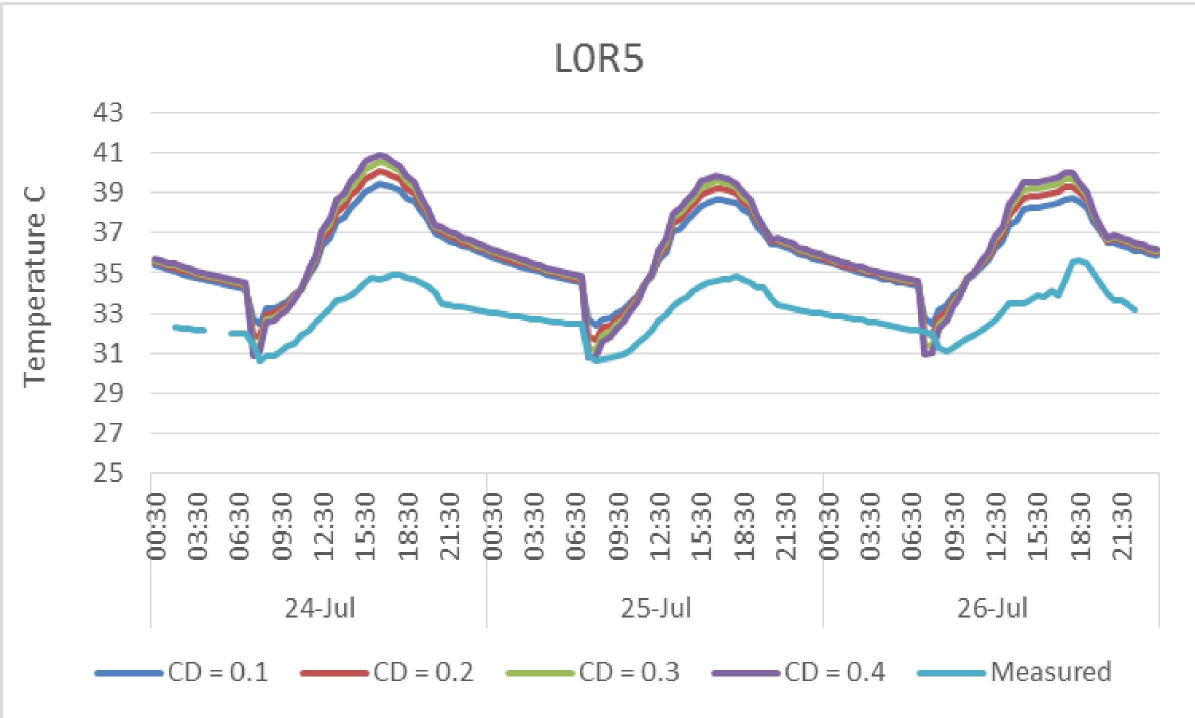


Figure 8.8: internal temperature of measured and modeled Aqaba house for different discharge coefficients.

Because no specific air-flow measurements were taken it was not possible to compare the predicted flow rates to reality. Without this information it's not possible to confirm whether the model was over predicting ventilation rates and thus contributing to a higher internal temperature. However an attempt was made to estimate the flow rate through an open terrace door that had no Venetian shutters in Casa Batroun. This was done by multiplying the measured air speed (m/s) at the door by the area (m^2) of the door to get volume flow rate (m^3/h). Although such approximation isn't accurate, interestingly, an agreement in the pattern of predicted and estimated flow rate was observed (Figure 8.9).

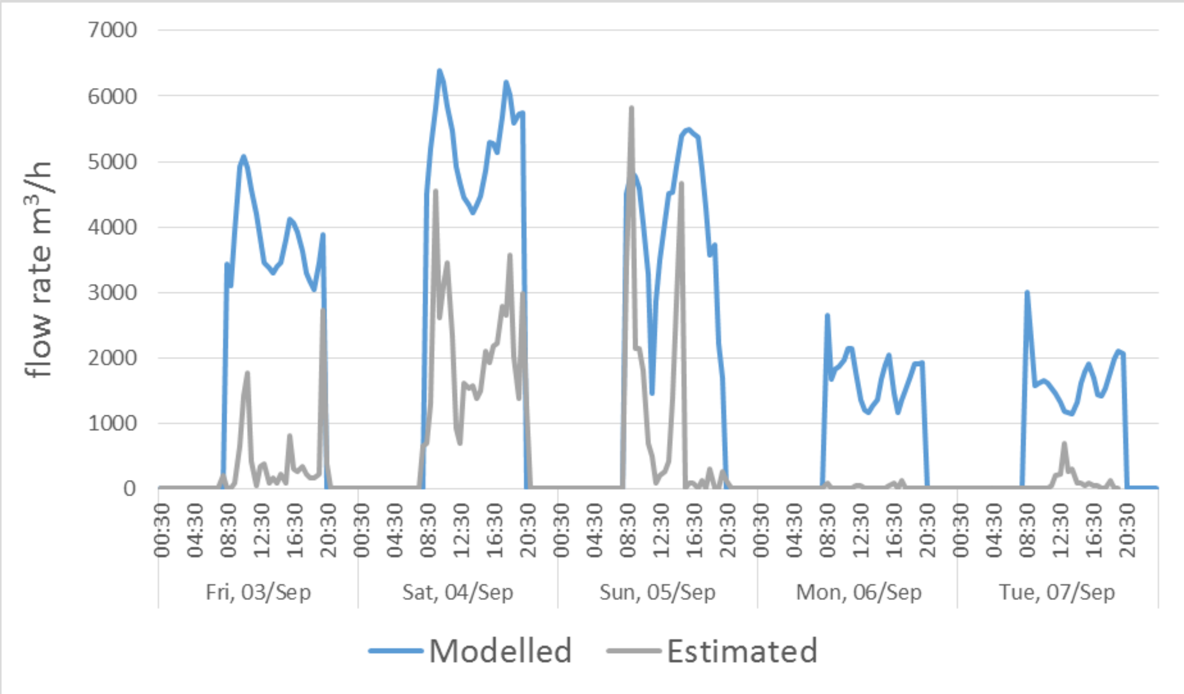


Figure 8.9: Estimated and modelled air flow rate through the terrace door on the 1st floor of Casa Batroun.

Other factors that could contribute to the discrepancy could be the unaccounted for internal thermal mass. Increasing the thermal mass of the walls (by increasing their material densities) beyond realistic values brought predicted and measured temperatures closer together, but a discrepancy still existed. The following is a review of studies that looked at similar cases, and discussed possible shortcomings of models:

A study by Johnson et al., (2011) reviewed four network airflow models namely; CONTAM, COMIS, EnergyPlus and ESP-r. The four models were found to predict nearly identical results of volume flow rates for wind and combined cross ventilation. The results were within 30% of measured values of volume flow rates. The authors identified two main shortcomings of network airflow models. The first is that wind turbulence in single sided ventilation cases is considered the main driving force but it isn't included in any of the studied models. This resulted in the wind pressure being treated as constant across openings at the same height. The second is model’s failure to predict bi-directional flow in horizontal openings such as roof vents or stairwells. This is because there was no significant change in height in a horizontal opening. They also indicated that the models seem to be less accurate in cases of large openings.

Zhai et al., (2011) compared the measured and modelled results of energyplus for three naturally ventilated buildings in the summer in northern Europe. They found that the measured and modelled results agreed only in one case where the building was only one storey, had very small openings, and had primarily glazed facades (very light weight construction). In another case, where the building was less glazed and had a heavier construction than the first case, the model over predicted internal temperatures on hot days; the study suggested that the coupling of thermal mass calculations with the airflow network may need improving as this factor was shown to have a significant impact on the results. This is because only increasing the thermal mass beyond what is realistic in the studied building improved the results.

Another possible shortcoming of the modelling is that the hygrothermal properties of materials were not simulated. Few of the materials used in the construction of both Aqaba and Casa Batroun were made of or contained natural fibres materials. Straw was added to the plaster of the external and internal wall surfaces of Aqaba house and several walls’ cavities were filled with mud and straw. The upper floor of Casa Batroun was constructed of timber and wood fibre insulation panels were used. Natural fibres have the ability to absorb and release moisture that affects heat flows through the materials as heat is released when moisture is being absorbed and absorbed when moisture is released (Hills et al., 2009). This Hygrothermal performance of materials is not accounted for in IES modelling. A study by Barclay et al., (2014) on Hygrothermal performance computer modelling of hemp-lime buildings found that the use of full-hygric simulation resulted in 0.6% reduction in the overheating hours in free-running hemp-lime building compared to IES results. Although a discrepancy of 0.6% seems insignificant, it is not clear how the hygrothermal properties of materials might affect the overheating hours in the studied buildings.

8.3 Summary

Several factors might have contributed to the discrepancy between simulated and monitored results, namely, inaccuracies in measurements discussed in Chapter 7, over predicting ventilation rates by IES, unaccounted for thermal mass, the coupling of the airflow network with the thermal model, and the unknown hygrothermal properties of the construction materials.

Despite the significance of the discrepancy between modelled and monitored data, it did not have a significant impact on the recommendations for appropriate day and night ventilation from Chapter 5. The buildings in reality performed better than the modelled results suggested. However, in the Aqaba building both NTV and DTV did not succeed in bringing internal temperatures below the upper comfort limit in July and August that was in agreement with Chapter 5 final recommendations. Similarly in Casa Batroun, in most rooms the internal temperature was equal or below the upper comfort limit for DTV in September and up to two degrees below the upper comfort limit for NTV, which was also in agreement with recommendations from Chapter 5.

Chapter 9: Conclusions

The overall aim of this thesis was to test the applicability of Givoni's Building Bioclimatic Charts to the EM region and establish whether they could be implemented as a pre-design environmental tool. The thesis assessed the suitability of the charts for day and night time ventilation appraisal. It was found that the cooling potential predicted by the BBCC did not agree with the cooling potential established through modelling of best-practice buildings. Based on the research and simulation conducted as part of this thesis, the following steps are suggested as guidelines to establish the suitability of natural ventilation as a cooling strategy for the EM region:

9.1 The Guidelines

First, designers should select the climatic zone, in which the building they are designing is located from the regional map (Figure 9.1). The suitable comfort boundaries may then be found in Table 9.1. Then Table 9.2 is used to determine whether natural ventilation in its two modes could be recommended as a cooling strategy. If either NTV or DTV or a combination of the two, could be recommended for the majority of the cooling season, urban and buildings layouts that encourage cross ventilation should be considered, additionally design guidelines for night ventilation are suggested in Table 9.3.

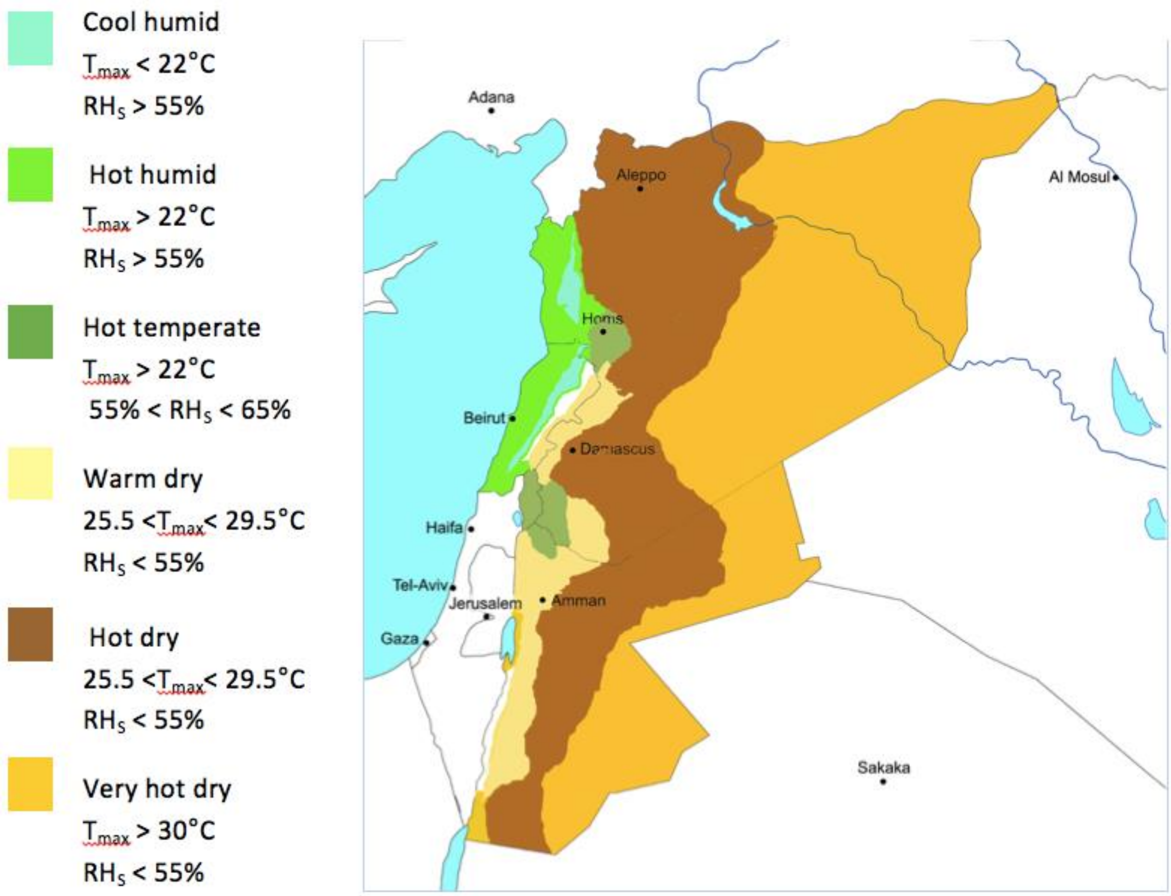


Figure 9.1: Eastern Mediterranean bioclimatic zoning, T_{max} is the mean temperature of the hottest month, RH_S is the corresponding average relative humidity

Table 9.1: Comfort boundaries

	Zone	*Hot humid*	*Warm dry*	*Hot dry*	*Very hot dry*
	Temperature (°C)	Beirut	Amman	Damascus	Aqaba
Apr	T_{om}	18.0	16.0	15.8	23.9
	T_{comf} upper limit	26.9	26.3	26.2	28.7
	T_{comf} lower limit	19.9	19.3	19.2	21.7
May	T_{om}	22.0	21.0	20.1	27.9
	T_{comf} upper limit	28.1	27.8	27.5	29.9
	T_{comf} lower limit	21.1	20.8	20.5	22.9
Jun	T_{om}	24.5	23.5	24.2	31.0
	T_{comf} upper limit	28.9	28.6	28.8	30.9
	T_{comf} lower limit	21.9	21.6	21.8	23.9
Jul	T_{om}	27.0	25.0	26.7	32.3
	T_{comf} upper limit	29.7	29.1	29.6	31.3
	T_{comf} lower limit	22.7	22.1	22.6	24.3
Aug	T_{om}	27.5	25.0	26.4	32.2

	T_{comf} upper limit	29.8	29.1	29.5	31.3
	T_{comf} lower limit	22.8	22.1	22.5	24.3
Sep	T_{om}	26.5	24.0	23.2	29.9
	T_{comf} upper limit	29.5	28.7	28.5	30.6
	T_{comf} lower limit	22.5	21.7	21.5	23.6
Oct	T_{om}	24.0	20.5	18.5	26.3
	T_{comf} upper limit	28.7	27.7	27.0	29.5
	T_{comf} lower limit	21.7	20.7	20.0	22.5

Table 9.2: Daytime and nighttime ventilation potential for cooling, percentage of overheating hours

Climate	Strategy	Apr	May	Jun	Jul	Aug	Sep	Oct
Hot dry	Day vent	0%	<10%	20-30%	40-50%	40-50%	20-30%	0%
	Night vent	N/A[1]	N/A	0%	0%	0%	0%	N/A
	Other cooling strategies required?	No	No	No	No	No	No	No
Very hot dry	Day vent	10-15%	30-40%	>50%	>50%	>50%	>50%	>50%
	Night vent	0%	<10%	30-40%	>50%	>50%	40-50%	<10%
	Other cooling strategies required?	No	No	Yes	Yes	Yes	Yes	No
Hot humid	Day vent	0%	0%	<10%	30-40%	50%	<10%	0%
	Night vent	N/A	N/A	<10%	<10%	<10%	N/A	N/A
	Other cooling strategies required?	No	No	De-humidification	De-humidification	De-humidification	No	No

Natural ventilation potential for the main climatic zones in the Eastern Mediterranean region could be conveyed simply to designers using the above graph. The graph was based on the extensive analysis carried out in Chapter 5. It is a very straight forward as it allows designers to quickly see the times of the cooling season where natural ventilation, in its two modes, is likely to be successful; and where additional cooling strategies are certainly needed. Unlike Givoni's charts, designers wouldn't need to plot monthly climatic lines or hourly weather data. Furthermore, no calculation of percentages of comfort time achievable is required.

[1] N/A not applicable: natural ventilation results in over cooling,

Table 9.3: Design recommendation for natural ventilation:

DESIGN RECOMMENDATIONS FOR NIGHT VENTILATION	REQUIRMENT
A design layout that encourages cross ventilation	6 air changes per hour are required
An insulated medium to heavy weight construction	Medium weight concrete blocks with internal plastering and external insulation
Solar gains acceptable up to 15 W/m^2 of floor area	Good shading design, using overhangs or Venetian shutters

These recommendations are based on the parametric analysis in Chapter 6 where medium weight concrete blocks with internal plastering and external insulation performed best for night ventilation. Similarly, night ventilation was feasible even when solar gains were up to 15 W/m^2 averaged over the following day in August, and internal heat gains were a modest 3 to 7 W/m^2. However, it should be noted here that subject, to other internal heat gains, this value might be higher or lower. By comparison, in the UK, the limit of solar heat gains that natural ventilation can cope with, is 25 W/m^2 provided that the average coincident internal gains over the day do not exceed about 15–20 W/m^2 especially in SE England (CIBSE AM10, 2005).

It is expected that by enabling designers to appreciate the full potential of natural ventilation for cooling through a simple graph and guidelines, more informed design decisions can be made. For example, where night ventilation is found to be a successful cooling strategy, design concepts that enable night ventilation while tackling concerns related to privacy and security could be developed.

9.2 Conclusions

The following is an evaluation of the main objectives of the thesis and reports to what extent these objectives were met:

1- Review existing bio-climatic design tools to establish a baseline in current practice

The literature review established the application and limitations of the BBCC and also identified gaps in the knowledge base. It was found that the distinction between developed and developing countries' comfort boundaries was not supported by research. Country-specific comfort zones and passive cooling boundaries should be established (Nicol, 2012). The extensive sampling required to establish the thermal comfort zone by survey, was restricted due to the continued conflict in the region for the duration of the thesis. As an alternative, the international standards based on the adaptive comfort theory were reviewed, and a comfort zone was suggested in Chapter 3 based on ASHRAE standards 2013. Additionally, a new bioclimatic classification for the region under consideration was established. It classified areas based on their summer temperatures and relative humidity, rather than temperatures and precipitation levels. The significance of this is that it created an alternative climatic zoning for the Eastern Mediterranean region that is more relevant for use in environmental appraisal.

2- Assess the suitability of passive cooling strategies for Eastern Mediterranean climates using Givoni's BBCC

This was done in two ways, firstly was by plotting monthly climatic lines for each bioclimatic zone in the region and secondly was by plotting hourly temperatures and moisture content from weather files for the three main climatic regions. This analysis showed that the results using these two methods did not agree. This meant that the most widely used method of plotting monthly climatic lines was unreliable; on the other hand the plotting of hourly data is a daunting task that will deter most designers from using the BBCC.

3- Select best practice domestic buildings as exemplars of 'well-designed' buildings and map passive strategies applied to those considered in the BBCC.

Current and vernacular best practice buildings in the region were reviewed, then two domestic buildings were selected for further modelling and monitoring. Their suitability to be naturally ventilated was assessed and the passive strategies they employed were mapped against the strategies in the BBCC. It was established that only the potential of daytime comfort ventilation and night time ventilation could be assessed.

4- Test the BBCC predictions for the selected passive strategies and buildings by dynamic building simulation.

Full building thermal performance analysis using dynamic modelling software IES VE 2013 was carried out for Aqaba city as representative of the very hot-dry climatic zone, Beirut city as a representative of warm-humid zone, and Damascus city as representative of a hot-dry zone. The performance of the modelled houses under DTV and NTV modes differed significantly from that predicted by the BBCC. Additionally, the modelling of the two houses in Damascus showed that there was up to 20% variation in the number of uncomfortable hours between the timber house and the masonry/concrete structures. The analysis also identified which ventilation strategies were effective in each region during the cooling season. It was demonstrated that in the hot dry region, a combination of both DTV and NTV was adequate to achieve thermal comfort.

5- Conduct a parametric analysis to establish how certain design parameters, mainly constructions and solar shading can affect the potential of passive cooling strategies

Typical wall constructions were modelled against those used in the selected best practice houses, with varying ventilation rates and solar gains for NTV in Damascus. It was found that the extra costs invested in the construction of the house in Aqaba, (very hot dry region), did not result in any additional benefit in the naturally ventilated scenario. However, an insulated medium weight construction was the most beneficial, it was also found that such constructions could tolerate up to 15 W/m^2 of solar heat gains.

6- Monitor the selected reference buildings and compare the findings to the above predictions

Both selected houses were monitored in summer 2013 when internal and external temperature and relative humidity measurements were taken, in addition to external environmental conditions. It was found that in the very hot dry region neither DTV nor NTV were suitable strategies in August, while NTV was successful in the hot humid region in September. These findings were consistent with the overall modelling recommendations, despite the measured internal temperature being three to four degrees lower than the modelling predictions.

7- Examine the performance gap between monitored and modelled results

The studied buildings were modelled again, using edited weather files to account for the onsite weather conditions and actual occupancy profiles. Discrepancies between the modelled and monitored results were examined. No conclusive reason could be identified, however, possible causes were discussed and appraised and a sensitivity analysis was conducted.

8- Suggest boundaries for the applicability of the selected passive strategies in the Eastern Mediterranean region

Boundaries based on BBCC were not suggested because it was demonstrated that the BBCC were limited in many ways. Firstly the suggested comfort zone, especially for developing countries, was shown not to be suitable. Secondly, as shown in previous chapters, the BBCC resulted in varying discrepancies for different climates. Instead, guidelines based on the analysis conducted in this thesis were suggested.

Analytical and experimental investigation has been undertaken such that this thesis not only examines existing Building bioclimatic charts and the potential for day time and night time natural ventilation as passive cooling strategies, but also provides guidance, on the most suitable strategies, and best design practice, for residential buildings in the near east Mediterranean region, to be conducive to operation in a passive manner.

The findings presented are expected to be of increased importance considering the recent unrest in the region and the extent of reconstruction envisaged over the next few years.

9.3 Future research:

In order to evaluate the likely use, implementation and potential benefit of the suggested guidelines, the findings of this thesis will be published in an open access interactive website; On-going evaluation of the proposed guidelines and zoning for the EM region will further validate the recommendations of this thesis.

The potential of other passive strategies such as evaporative cooling needs to be assessed, and this can be can be undertaken based on the zoning and some of the data processing techniques developed in this work.

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Appendix B

5 SPECIFICATION

This Specification relates only to Option 1, 2 and 3 WindSonic Sensors fitted with a Red Tab adjacent to the North Marker arrow and Serial Numbers 08100001 onwards.

Output		
Units of measure	Metres/second (m/s), Knots, Miles per hour (mph), Kilometres per hour (kph), Feet per minute (fpm)	
Output frequency	0.25, 0.5, 1, 2, or 4 outputs per second	
	Digital	Analogue
Parameters	Polar - Speed and Direction UV - 2 axis, signed Speed NMEA Speed and Direction Tunnel - U speed & U Polarity	Polar - Speed and Direction UV - U Speed and U Polarity NMEA – Speed and Direction Tunnel - U Speed & U Polarity
Wind Speed		
Range	0 – 60m/s,	0 – 5m/s, 0 – 10m/s, 0 – 20m/s, 0 – 30m/s, 0-40m/s, 0 – 50m/s, 0 – 60m/s
Accuracy	± 2% (at 12m/s)	± 2% (at 12m/s)
Resolution	0.01 m/s	10 bits
Wind Direction		
Range	0 - 359°	0 - 359° Or 0 - 539° (Wraparound mode)
Accuracy	± 3° (at 12m/s)	±3° (at 12m/s)
Resolution	1°	1°
Analogue output formats		
0-5V 4-20mA 0-20mA	± 1% of full scale N.B. Analogue output impedance = 1KΩ (V out) Load resistance between the Analogue outputs (Pins 8 & 9) and Signal Ground (Pin 1) must be <= 300 ohms, including cable resistance.	
Digital output formats		
Gill	Continuous or Polled (output on request by host system) Polar (Speed and Direction) or UV (2 axis, signed Speed)	
Marine – NMEA	NMEA 0183 version 3	
Communication formats		
WindSonic Option 1	RS232	
WindSonic Option 2	RS232, RS422, RS485	
WindSonic Option 3	RS232, RS422, RS485, and Analogue	
Baud Rate	2400, 4800, 9600, 19200, 38400 Baud	
Anemometer status	Status OK and Error codes included in output message	

Environmental	
Moisture protection	IP65
Temperature	Operating -35°C to +70°C Storage -40°C to +80°C
Humidity	Operating <5% to 100%
EMC	EN 61326
Standards	Manufactured within ISO9001: 2000 quality system

Power requirement	5 – 30 V DC Option 1 and 2 units. 7 – 30 V DC. Option 3 unit. Current drain depends on variant i.e. RS232 approximately 9mA rising to 44mA for Analogue variant. Lowest power consumption is obtained with the following configuration:- M2, P20, B3, S9 (approximately 5.5mA at 12v).
Mechanical	
Size / weight	142mm diameter x 160mm 0.5kg
Mounting	Pipe mounting 1.75 inches (44.45mm) diameter
Material	External - Acrylate Styrene Acrylonitrile, Polycarbonate blend.

The Specification for the Option 4 SDI-12 unit is detailed in Section 14.

Appendix C

Vortex Cup Anemometer

Accuracy - 0.22 m/s from 1.78 to 4.47 m/s, +/-4% from 4.47 to 22.35 m/s

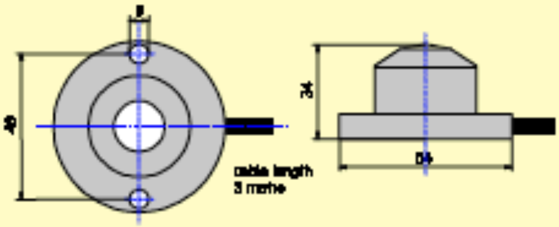
SENSOR TYPE	3-Cup rotor Reed switch/magnet provide 1 pulse per rotation.
OUTPUT for D2 Rotor	1 pulse per rotation 2.5 mph per Hz
ROTOR DIAMETER	approx. 5 in (~125 mm)
SPEED RANGE	approx. 3 mph to 125+ mph (~5 kph to over 200 kph)
MOUNTING BRACKET	Supplied with an aluminum mounting bracket with 2 holes for screws. Designed to be mounted on top of a pole or bracket.
WIRE	Standard length is 25 feet (8m) custom lengths available upon request - tested OK to over 1,500 feet
DISPLAY	Formula for converting pulses to speed: 2.5 mph per Hz (2.5 mph per pulse/second)

Appendix D

SP *LITE*

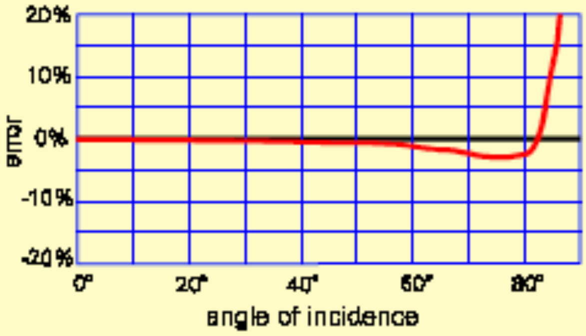
Silicon Pyranometer

Dimensions

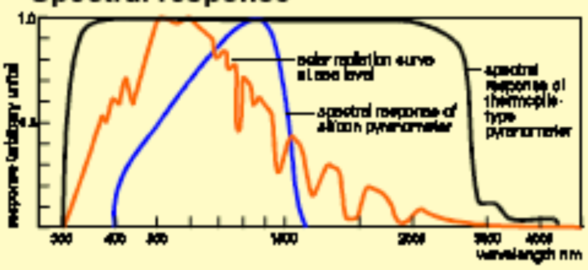


Dimensions in mm.

Directional response



Spectral response



Specifications

Sensitivity (nominal):	100 µV/Wm^{-2}
Spectral response:	equals silicon
Temperature range:	-30 °C to +70 °C
Response time:	less than 1 sec
Range:	+2000 Wm^{-2}
Temperature dependence:	± 0.15 %/°C
Directional error : (up to 80 degrees)	< 10%
Spectral range:	0.4 - 1.1 micron

Recommended use:
SP *LITE* is designed for routine measurement of solar radiation.
It is especially designed for:

- Photo Voltaic / solar energy module monitoring
- agricultural evapotranspiration estimation
- air pollution dispersion calculations using the Delta-T method
- educational purposes

SP *LITE* can be used under all weather conditions. The sensor measures the solar energy received from the entire hemisphere.
SP *LITE* is ideal for measuring available energy for use in solar energy applications, plant growth, thermal convection and evapotranspiration.

SP *LITE* uses a photodiode detector, which creates a voltage output that is proportional to the incoming radiation. Also due to the unique design of the diffuser, its sensitivity is proportional to the cosine of the angle of incidence of the incoming radiation, allowing for accurate and consistent measurements.

SP *LITE* is easy to use. It can be directly connected to voltmeter or data logger. Direct readout in Watts per square meter (Wm^{-2}) can be derived from the measured voltage divided by the calibration coefficient.

The **SP** *LITE* Silicon Pyranometer compares favourably to ISO 9060-specified First Class Thermopile Pyranometers under clear & unobstructed natural daylight conditions, and fully complies with CE Directives.

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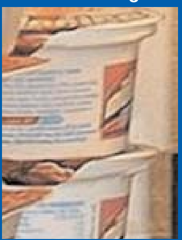
Appendix E

RTcom™-xxx-IDT Integrated Temperature Transmitter

Fishing Industry

Ripening

Bulk Storage



Chilled Food

Pharmaceuticals

Road Transport

Manufacturing

INTRODUCTION

The RTcom™xxx-IDT is a proven and highly cost effective modern alternative to manually recording room, freezer and refrigerator temperatures. The -IDT combines integrated digital temperature technology, battery management, an integrated thermal delay and state-of-the-art ASIC wireless technology within a single sealed for life package.

Protected from the outside world by a food safe plastic jacket, followed by a layer of potting compound, the transmitter achieves a level of sealing exceeding the IP68. Hence, the -IDT can be easily washed, cleaned and is resistant to most chemicals and solvents. This makes the -IDT ideal for use wherever food and pharmaceuticals are being processed, stored or transported. It is also suitable for use in server and clean rooms.

The advantage of the -IDT over probe and cable based systems are numerous. There are no holes to drill to pass cables, eliminating the risk of contamination and there are no cables to secure which are difficult to clean and move. The other and not so obvious advantage is its unique addressing system, this permits the transmitter to double as a RFID tag, identifying trailers and pallets into which it is buried.

In practice the wireless communication distance / range can be anything from a few tens of meters to over 200m. This entirely depends upon the application and the level of screening offered by the packaging / container etc. Where range requires enhancement a low cost booster station is available.

Specification

- -40C to + 70C operation
- 0.5C Accuracy -10 to + 70C
- Sealed for life IP68 construction
- Integrated digital transducer for temperature
- Integrated antenna
- Measures 115 or 170 x 36 x 40 mm
- Unique address/serial number
- High reliability Wide Band FM modulation
- Low power radio - 100% EMC safe
- Radio Approvals EN-300-220-1
- Integrated cable tie / mounting bracket
- 3-Years to 10-years battery life dependant upon sample / transmission rate selected.

The -IDT is fully compatible with our Radio Data Loggers, or PC based Serial Data Receivers and Cellular Hub GPRS Data Concentrators and Repeater Stations.

Battery life is typically from between 3 and 10-years depending upon the read and transmission rate ordered. Low battery warning is included and the receivers offer transmitter failure alarms and high/low alarms. Data output from our receivers is in an open protocol ASCII format suitable for import into MS Excel.

Order Code Examples

RTcom™-xxx-IDT - (col) - (ln) - (s)

Where xxx = operating frequency
col = colour WH = White, BL = Blue. Other colours to order.
ln = length of transmitter + antenna: 115mm or 170mm
s = transmit repetition rate: 1m, 5m, 15hr

Accessories Available

Plastic 12mm Stand-off Wall Mounting Clip
Stainless Steel 150mm Wall clip
Repeater / Booster Stations
Radio Data Loggers & PC Receivers with CSV file generation software

Radio-Tech Limited, Radio House, The Old Brewery, Lindsey Street, Epping, Essex, ENGLAND CM16 6RD
Telephone: UK +44(0)1992 576107 Fax +44(0)1992 561994. e-mail sales@radio-modem.com
http://www.radio-tech.co.uk

Issue 2/05

Appendix F

Halma Water Management

RADIO-TECH

Building Performance

Ecosense

• Flow Measurement • Data Logging • Leak Detection • Pressure Control • Environmental Monitoring • AMR • Energy Management

Ecosense

Radio-Tech's Ecosense is a battery powered, intelligent temperature and humidity sensor originally designed for the Energy Saving Trust to evaluate the insulation of new housing, although the sensors are suitable for all types of dwellings. Available for internal or external or applications.

The sensor is available in three versions: internal, external (reading both temperature and humidity) and surface (reading only temperature conducted through a wall). The dual sense allows you to monitor temperature and humidity indoor or out as well as providing a solution for weather proof data collection.

The sensor chirps at regular intervals, typically every five minutes (unless a different specification is requested) and transmits the data to the RT:Wi5 data hub or Modbus receiver. This information is then sent directly to the relevant server.

Since Ecosense's sensors are radio based and needs no connection to mains electric power, the sensors can be easily installed. The unit is powered by a lithium battery that lasts up to three years

KEY BENEFITS

- Wireless
- Fully calibrated
- Simply mount on wall
- Up to 3 years battery life
- Weather proof enclosure available
- Internal and external models available
- Meets Energy Saving Trust specification

A HALMA COMPANY

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ISO 9001 REGISTERED UKAS MANAGEMENT SYSTEMS

ISO 14001 REGISTERED UKAS MANAGEMENT SYSTEMS

Halma Water Management

Halma Water Management

RADIO-TECH

Building Performance

ecosense

Technical Data	
Radio frequency	433.92MHz
Power Output	5dBm
Operating Temperature	-10°C to +55 °C
Temperature accuracy	<0.3 °C
Resolution	0.01 °C
Relative humidity accuracy	<3 % RH
Resolution	0.01% RH

Order Codes	
434MHz	**Temperature and Humidity Transmitter**
314-001	Temperature Transmitter -10C to +55C with integral sensor
314-003	Temperature Transmitter -30C to +55C with 1.8m probe sensor
383-015	Humidity Transmitter, external probe mounted RH sensor 500mm cable
383-013	Humidity Transmitter, external probe mounted RH sensor 2m cable
399-003	Temperature Transmitter PT100 external 2m probe
399-002	Temperature Transmitter PT100 external 3m probe

• Flow Measurement • Data Logging • Leak Detection • Pressure Control • Environmental Monitoring • AMR • Energy Management

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